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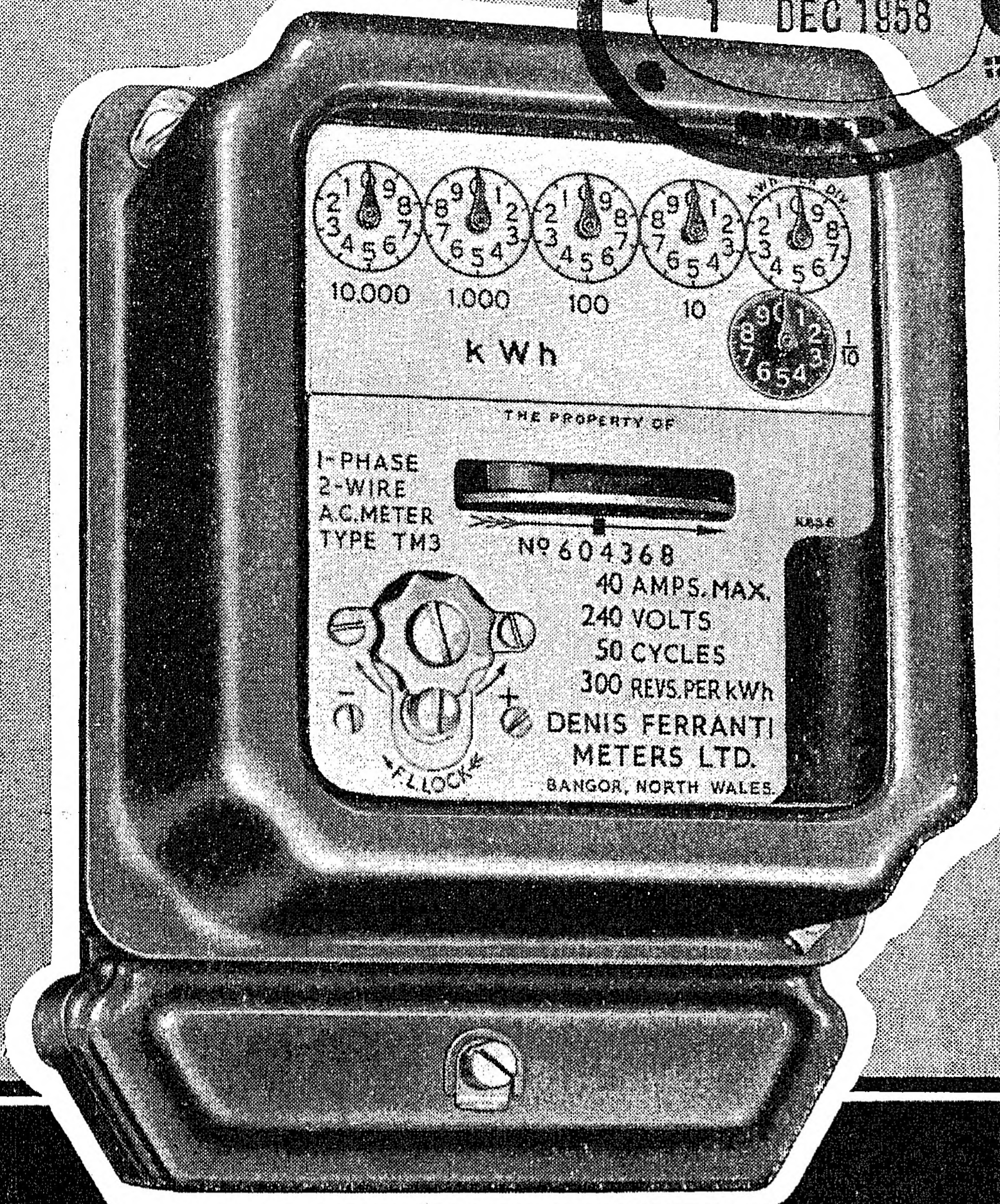

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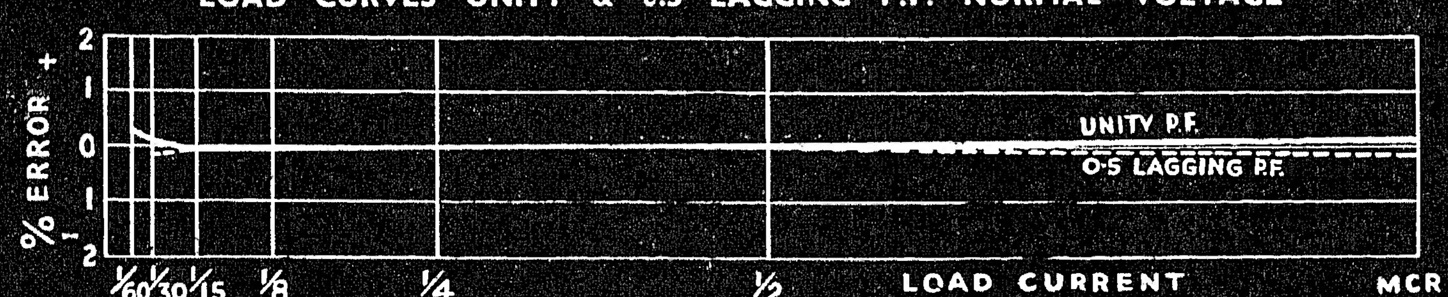

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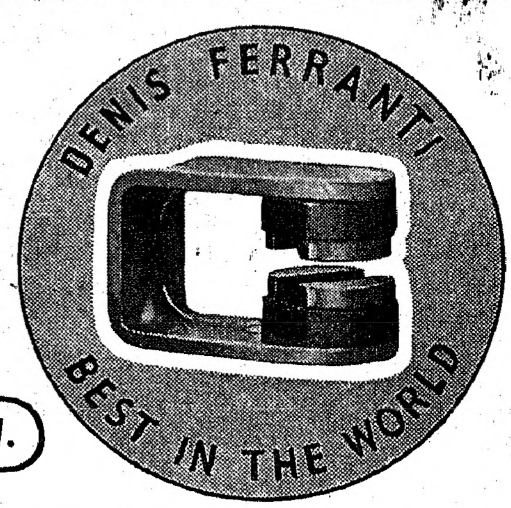

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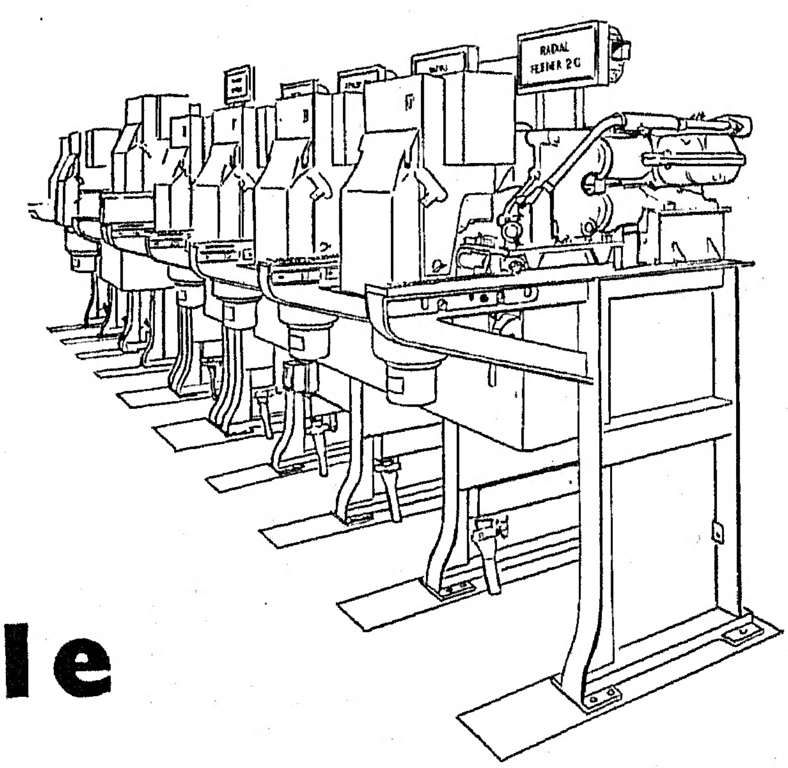
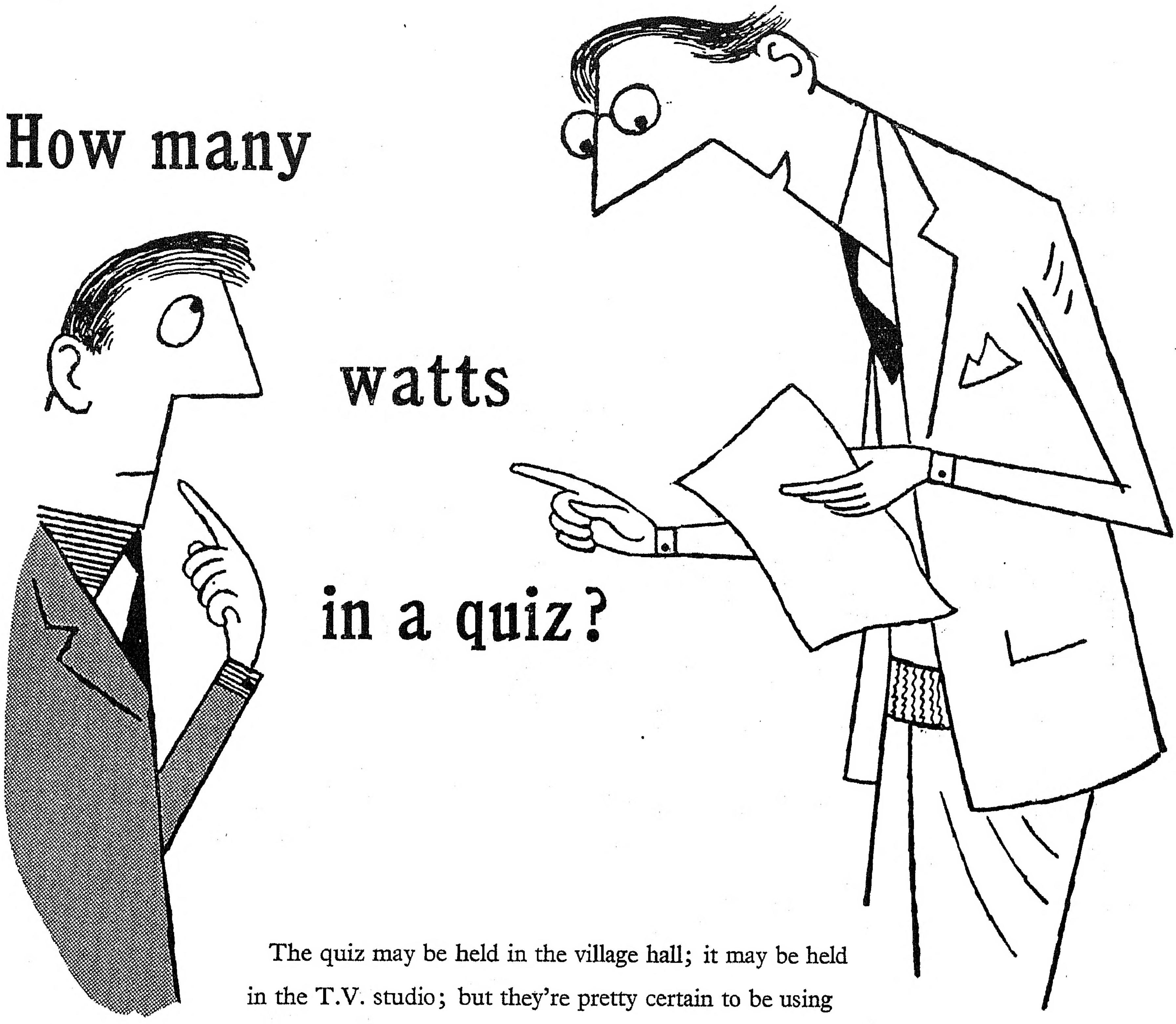


How many watts in a quiz?



The quiz may be held in the village hall; it may be held in the T.V. studio; but they're pretty certain to be using electricity in one way or another. Watts are getting to work, and, between power station and consumer, probably half a dozen people are keeping a careful watch on them.

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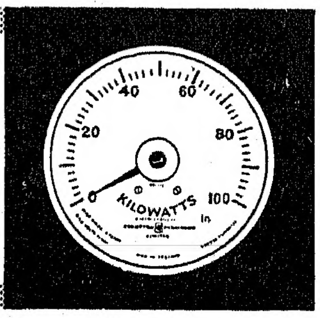

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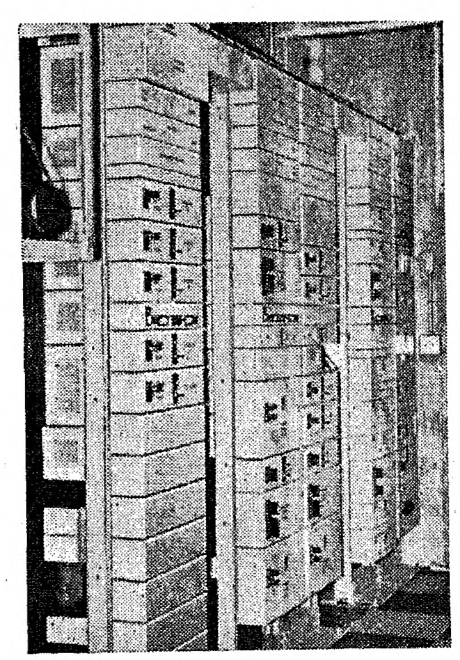

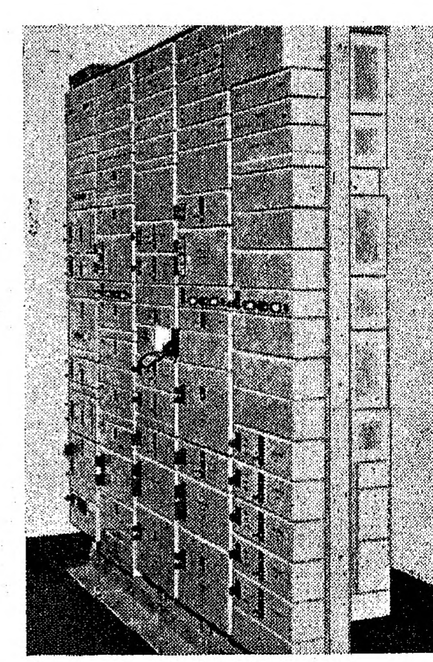

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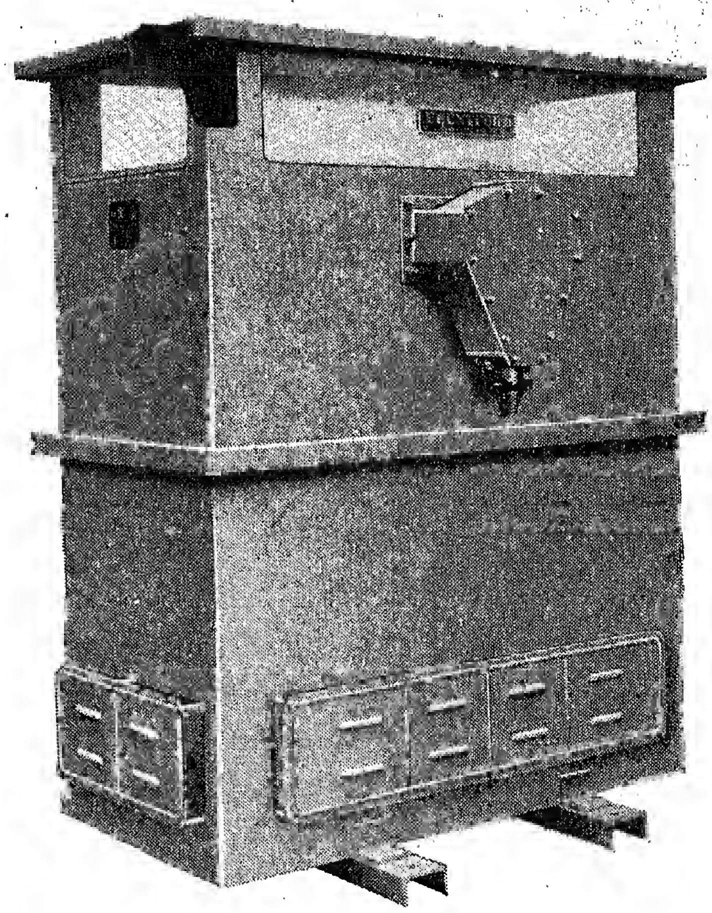

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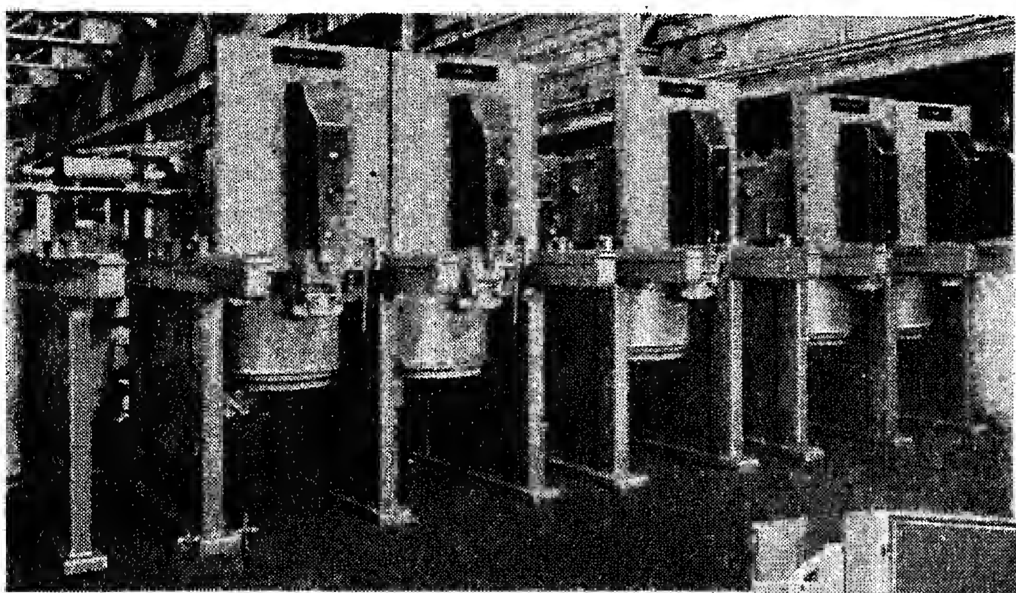
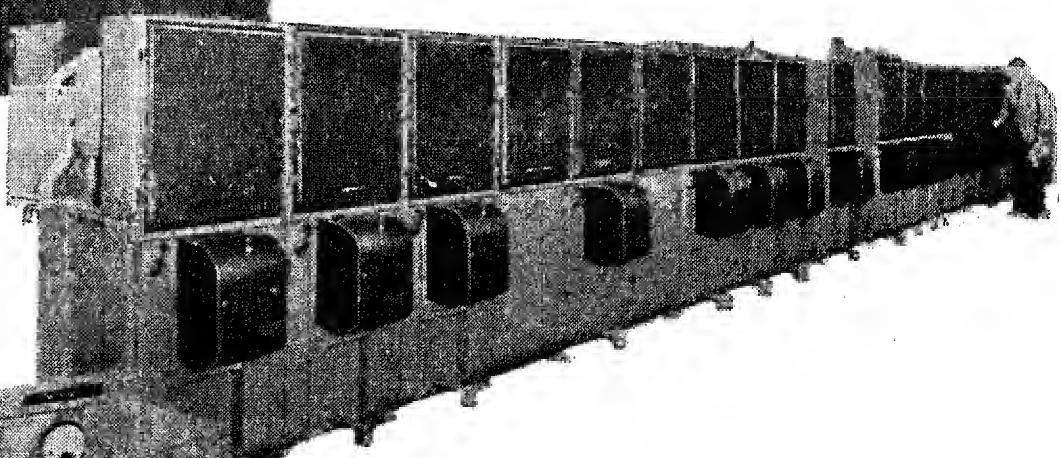


Five-panel, 22-kV, 500-MVA solenoid-operated switchboard for the control of the incoming feeders (from the Tata Power Co., Ltd.) and 7,500-kVA transformers which supply electric power to the whole refinery.



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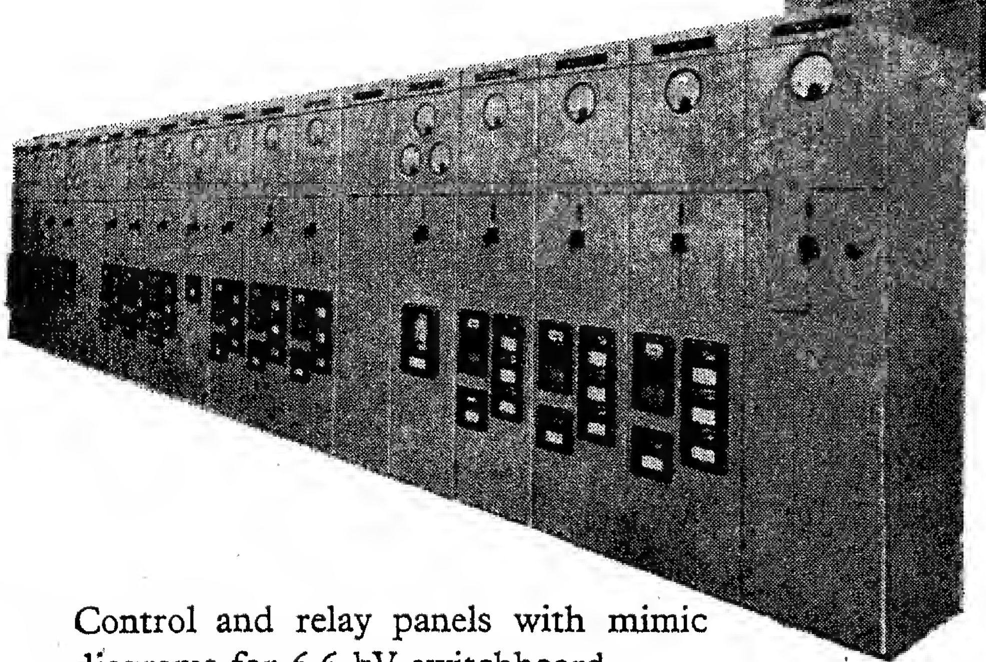

Control and relay panels with mimic diagrams for 6.6-kV switchboard.

Manufacture is now proceeding with a further two 22-kV, and nine 6.6-kV, units for a third 7,500-kVA transformer and additional refinery feeders; BTH have also supplied a total of eighty-three 6.6-kV, 150-MVA hand-operated metal-clad switchgear equipments for the refinery substations.

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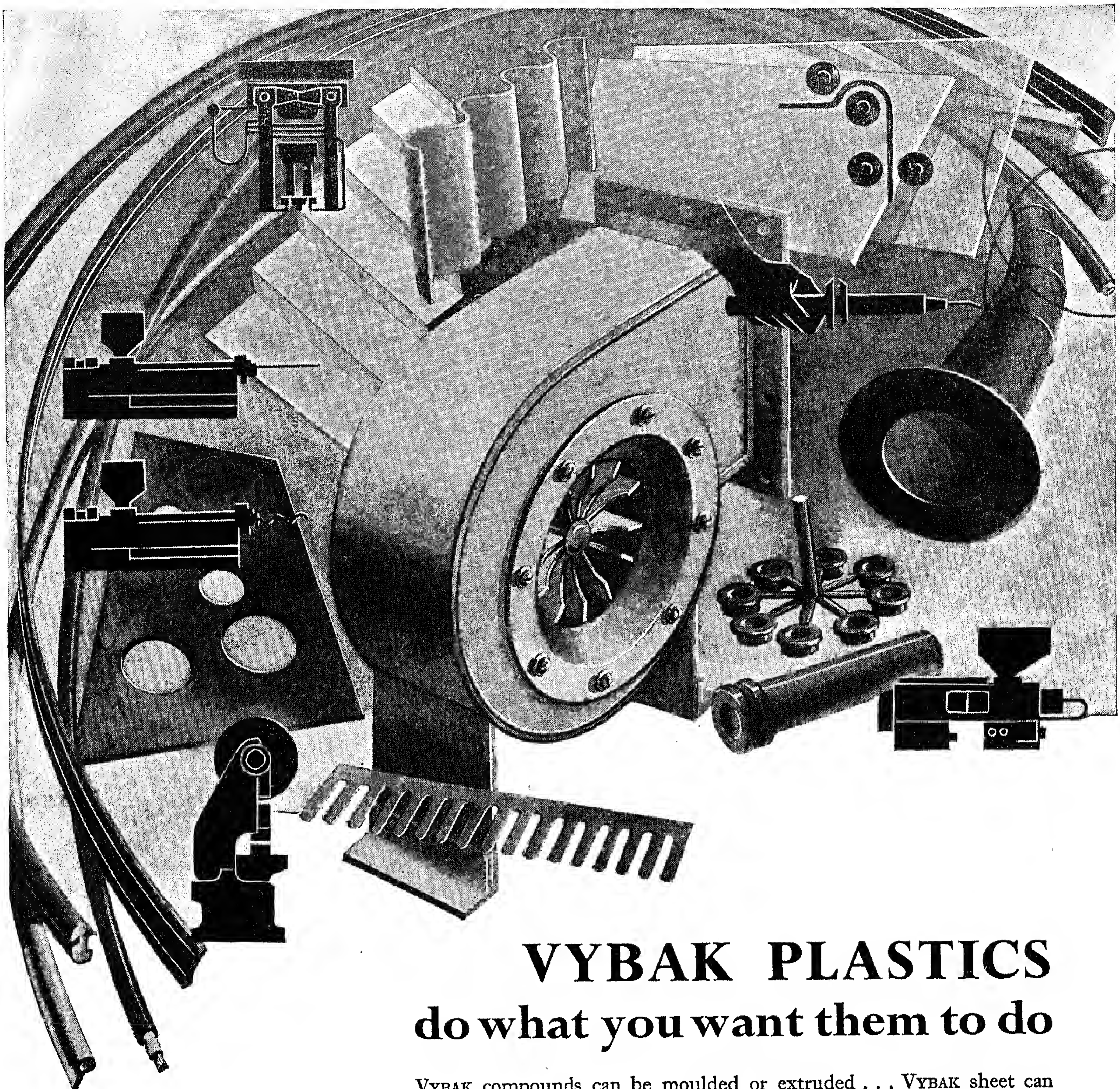

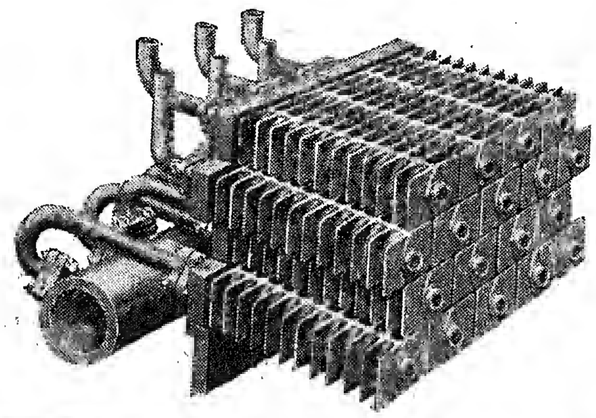

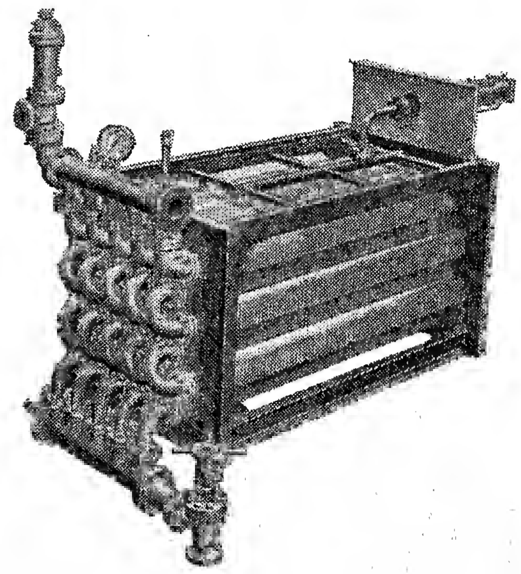

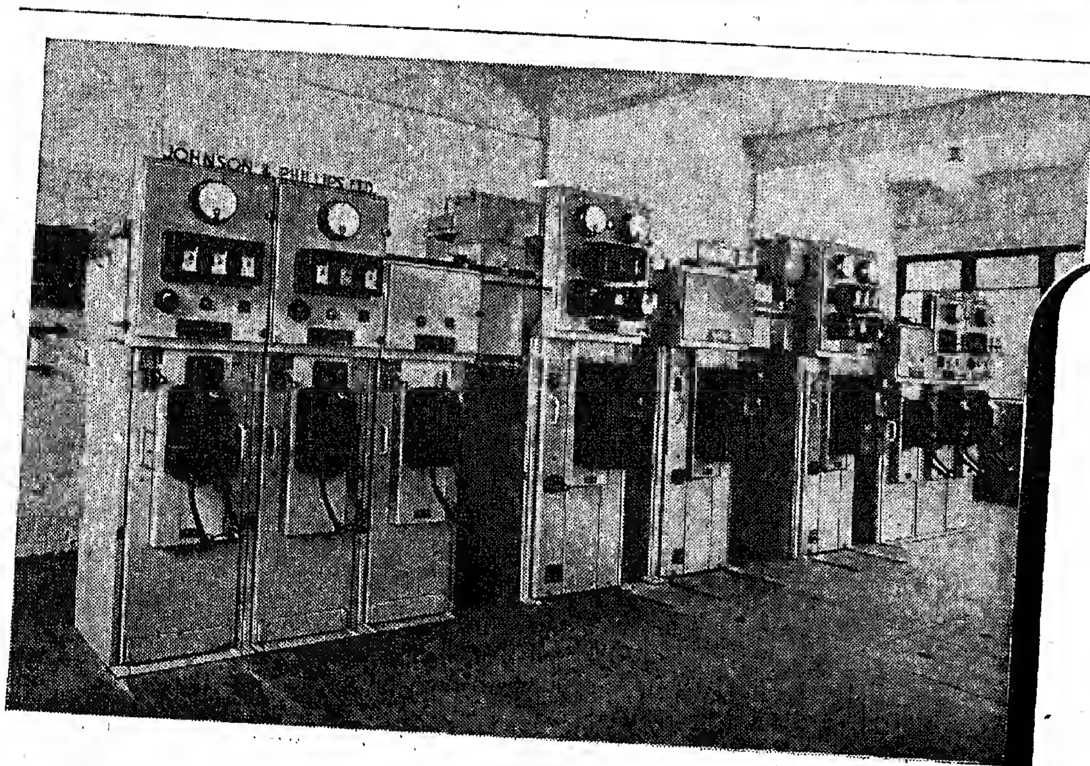
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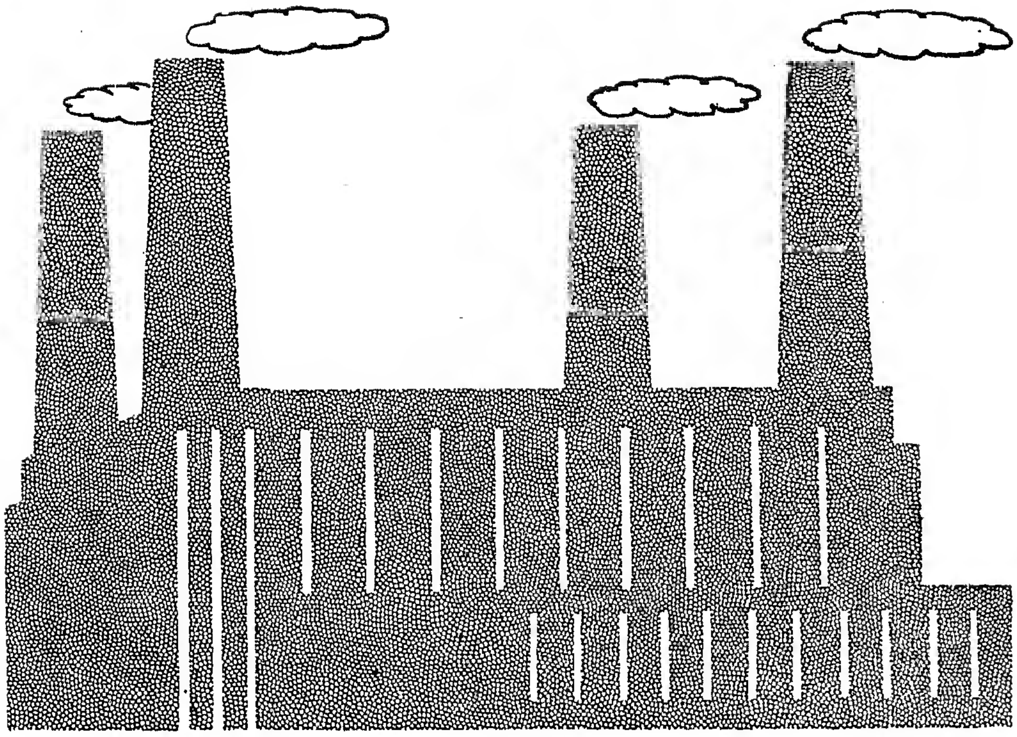

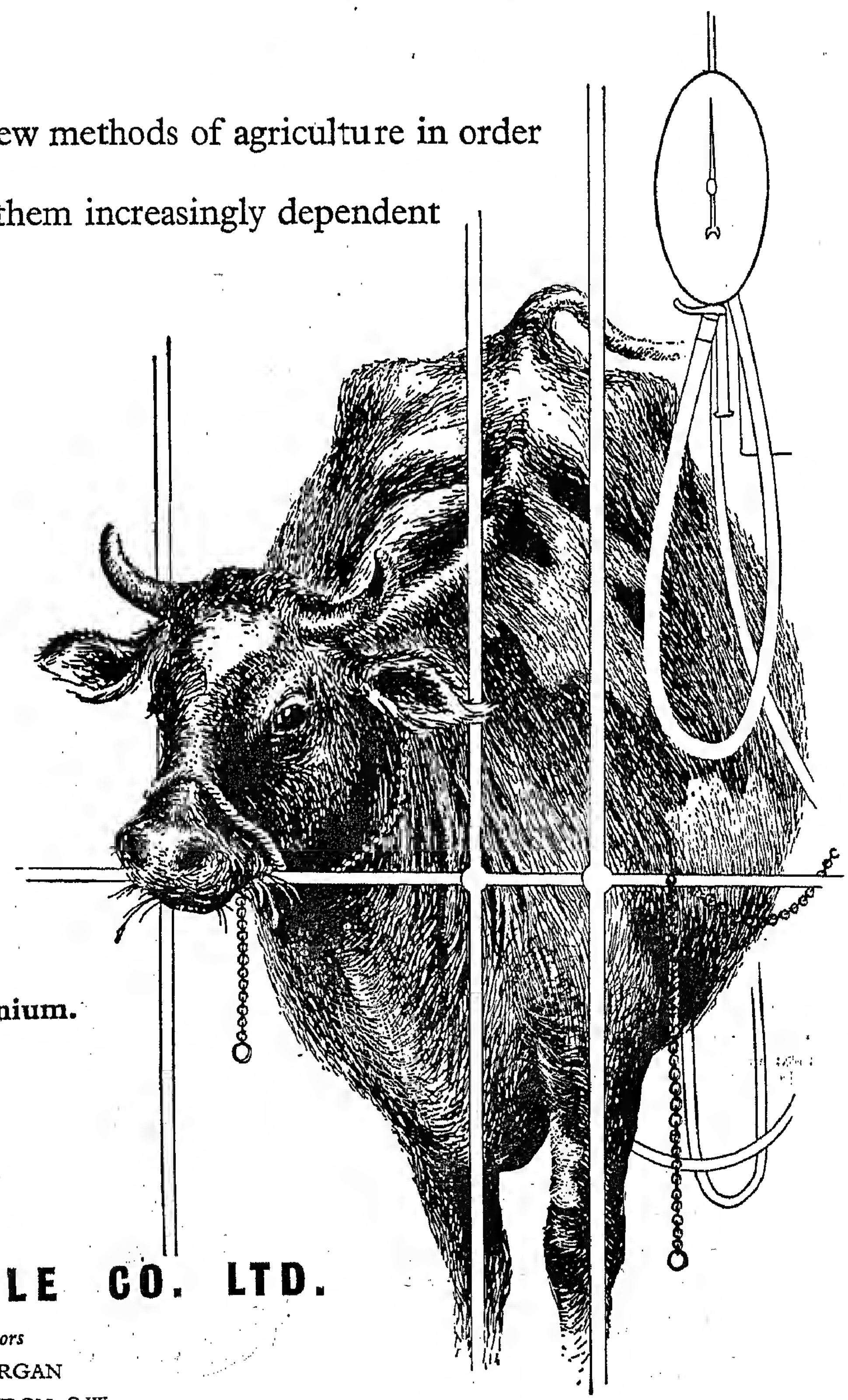

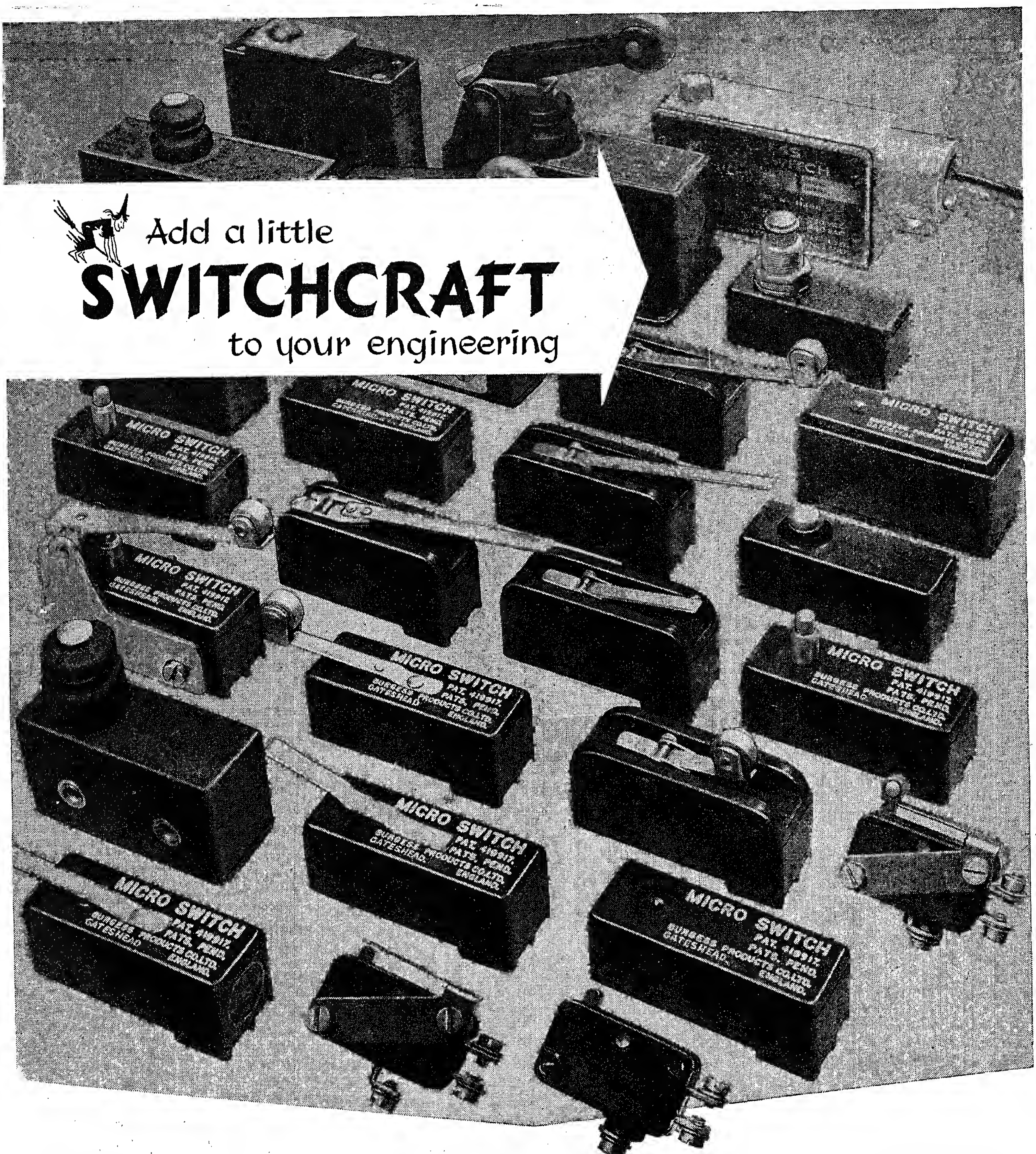
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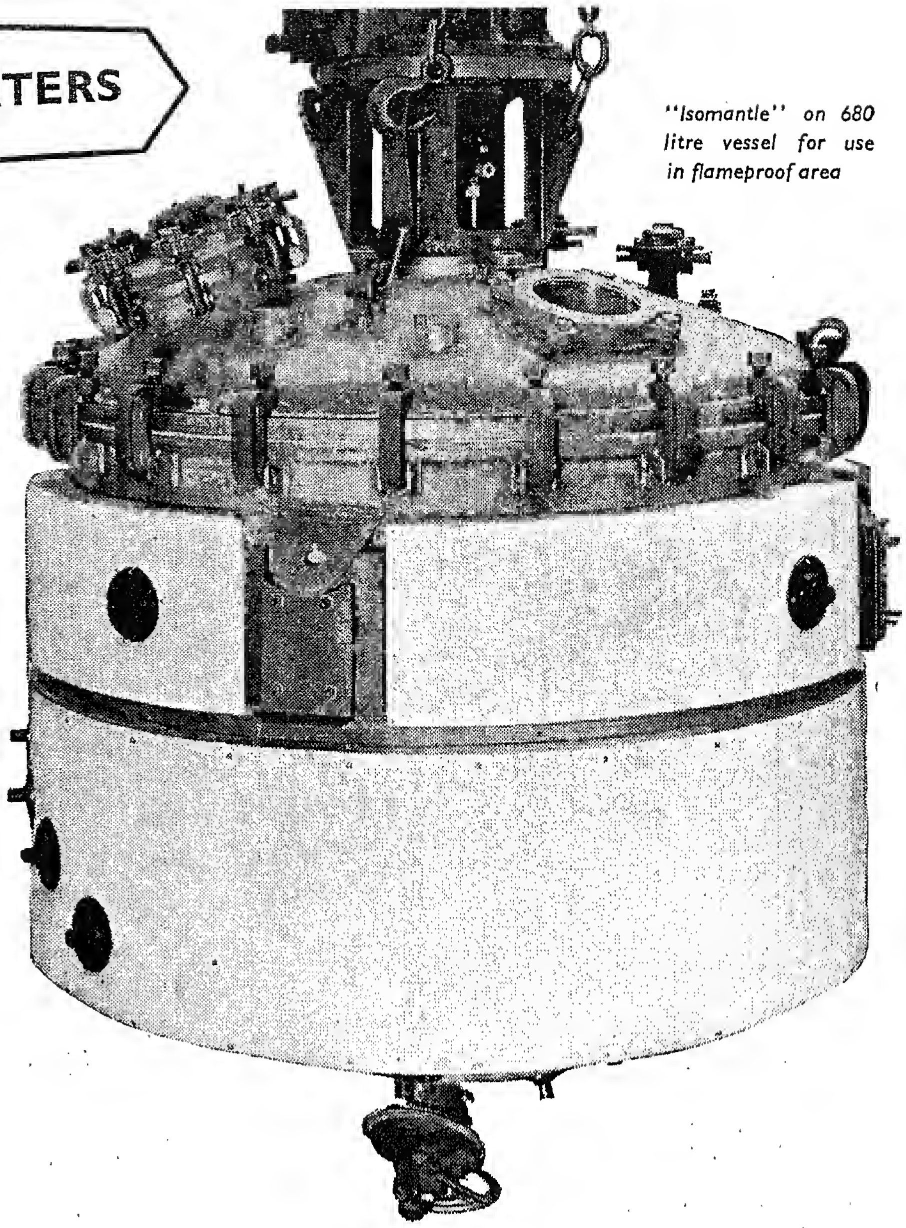

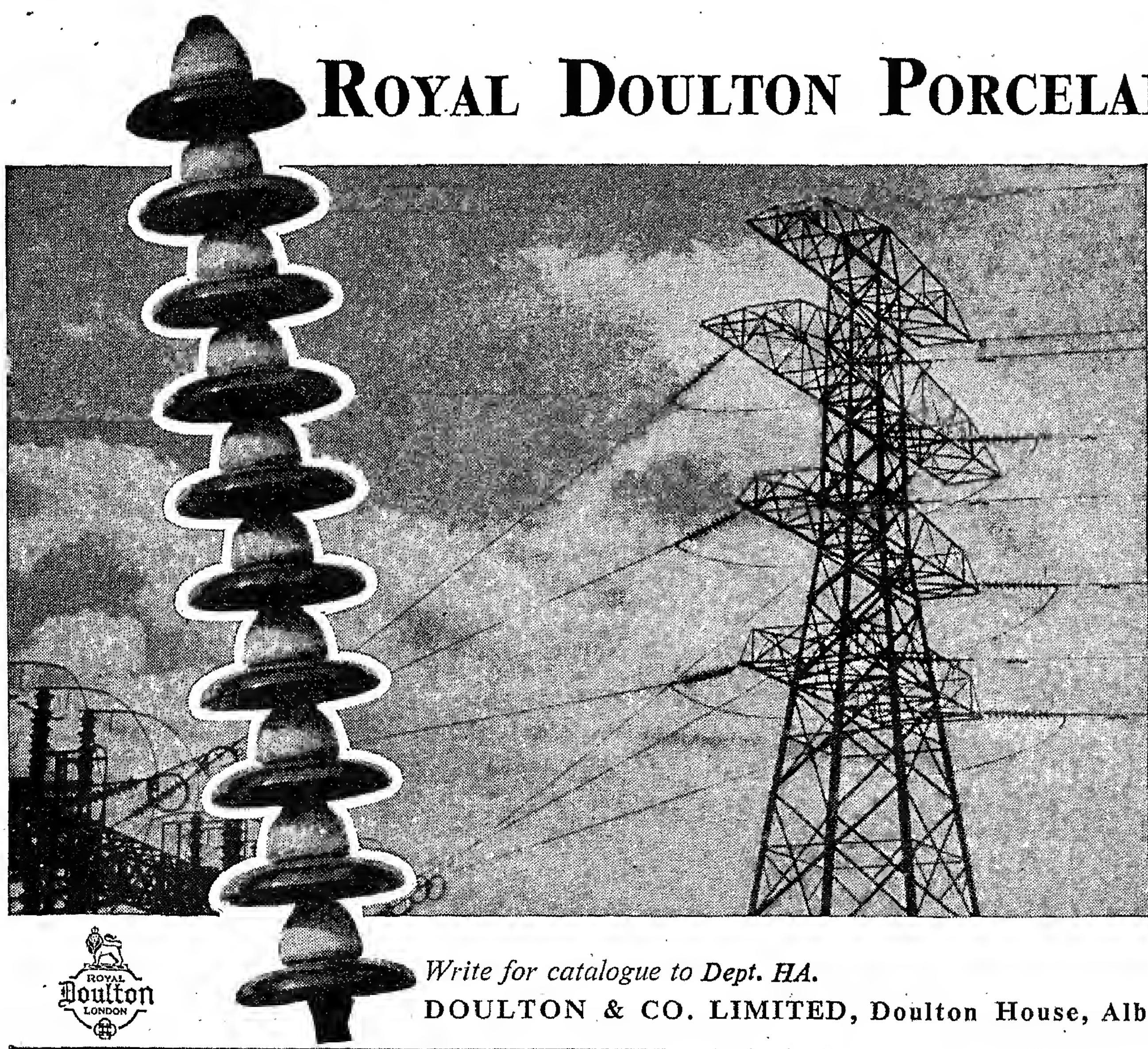

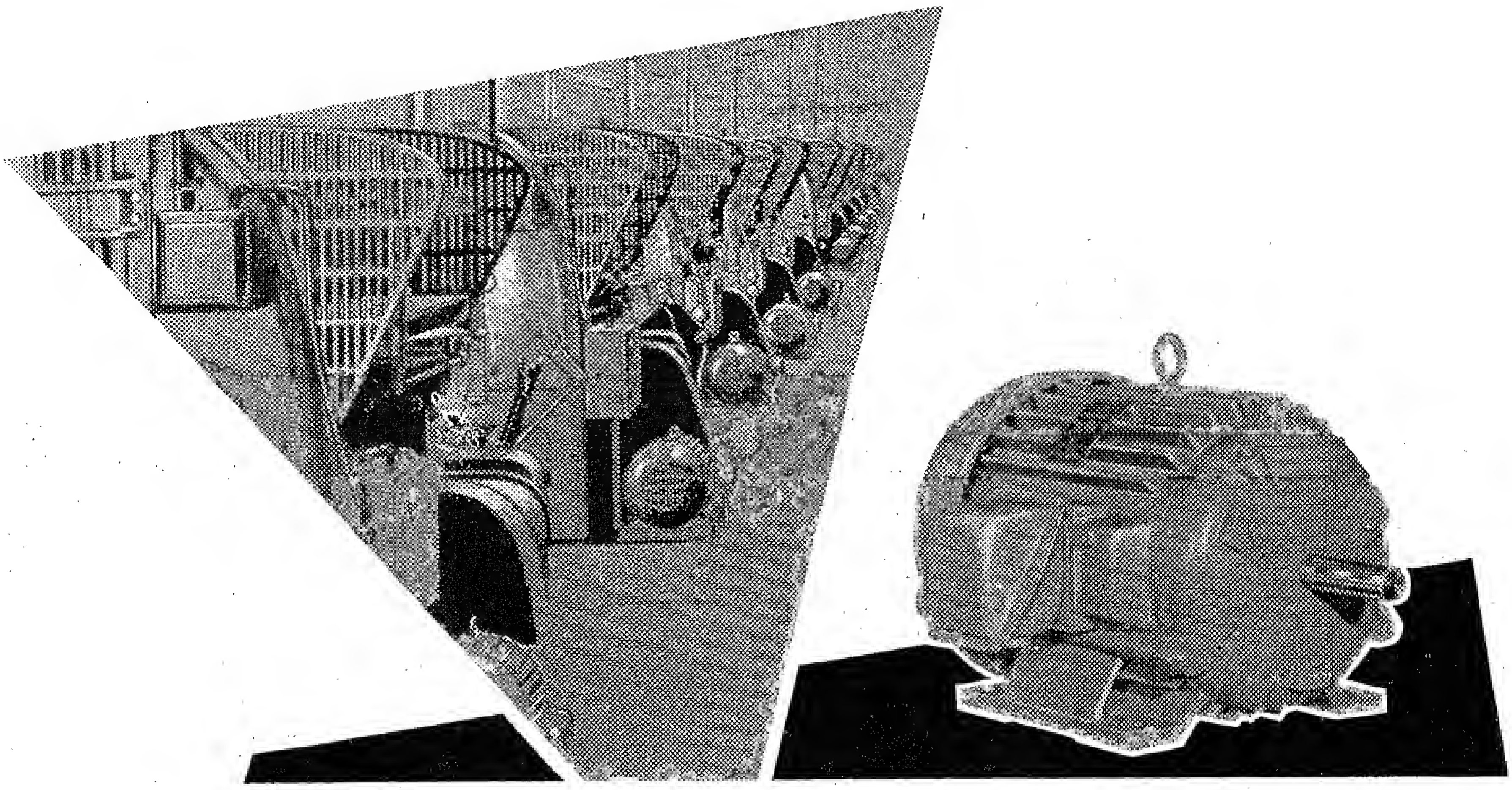

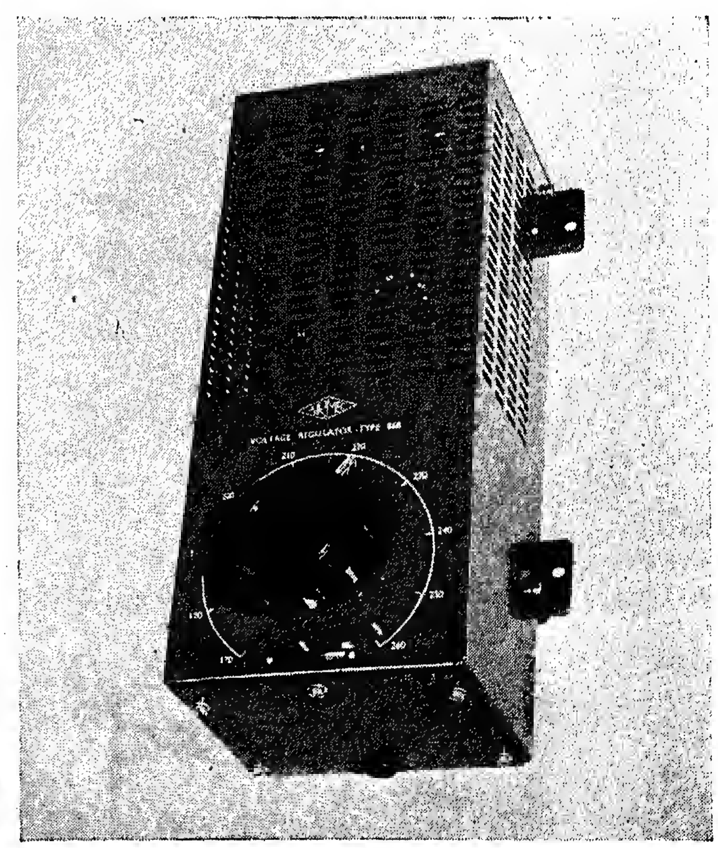

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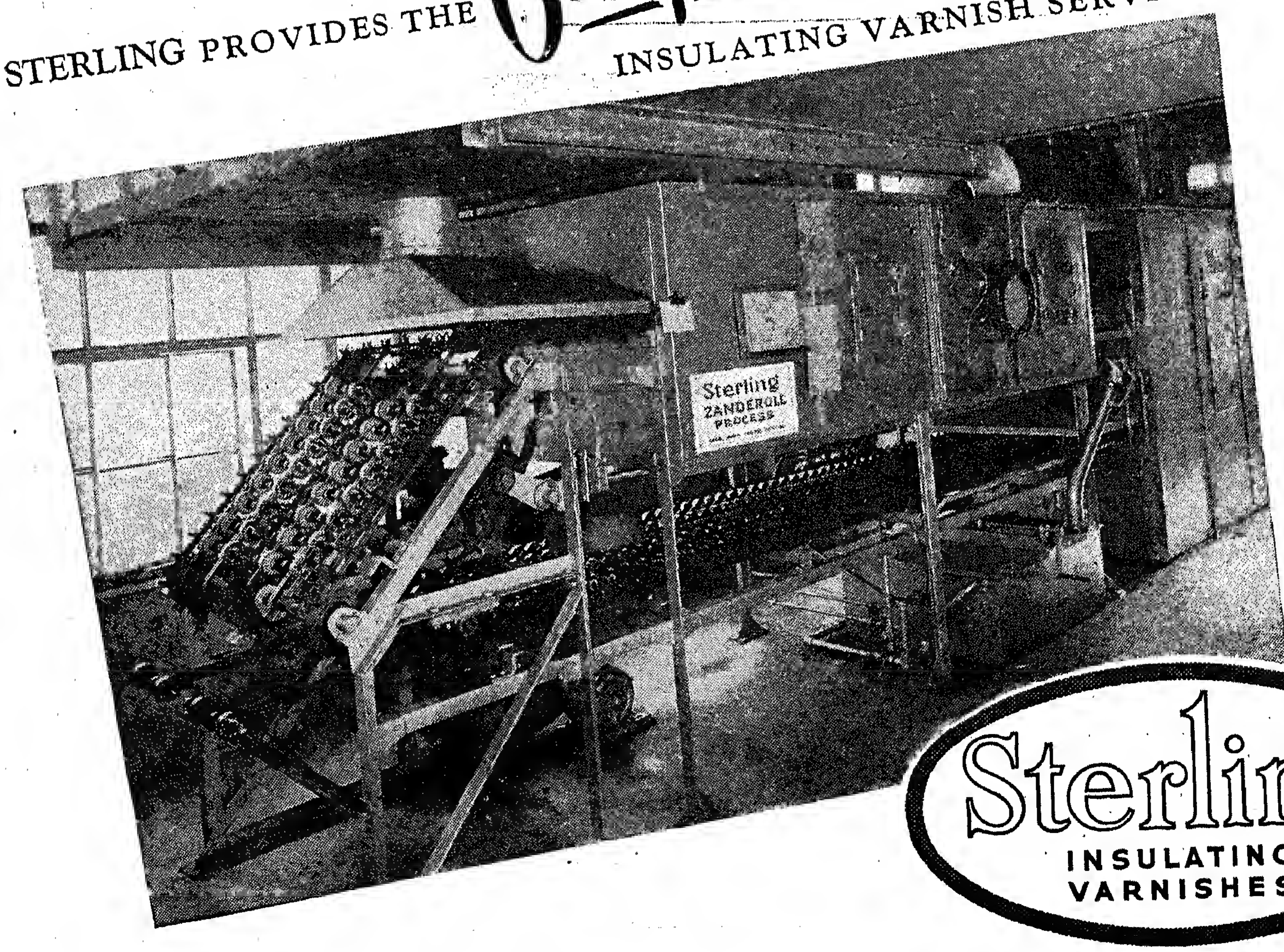

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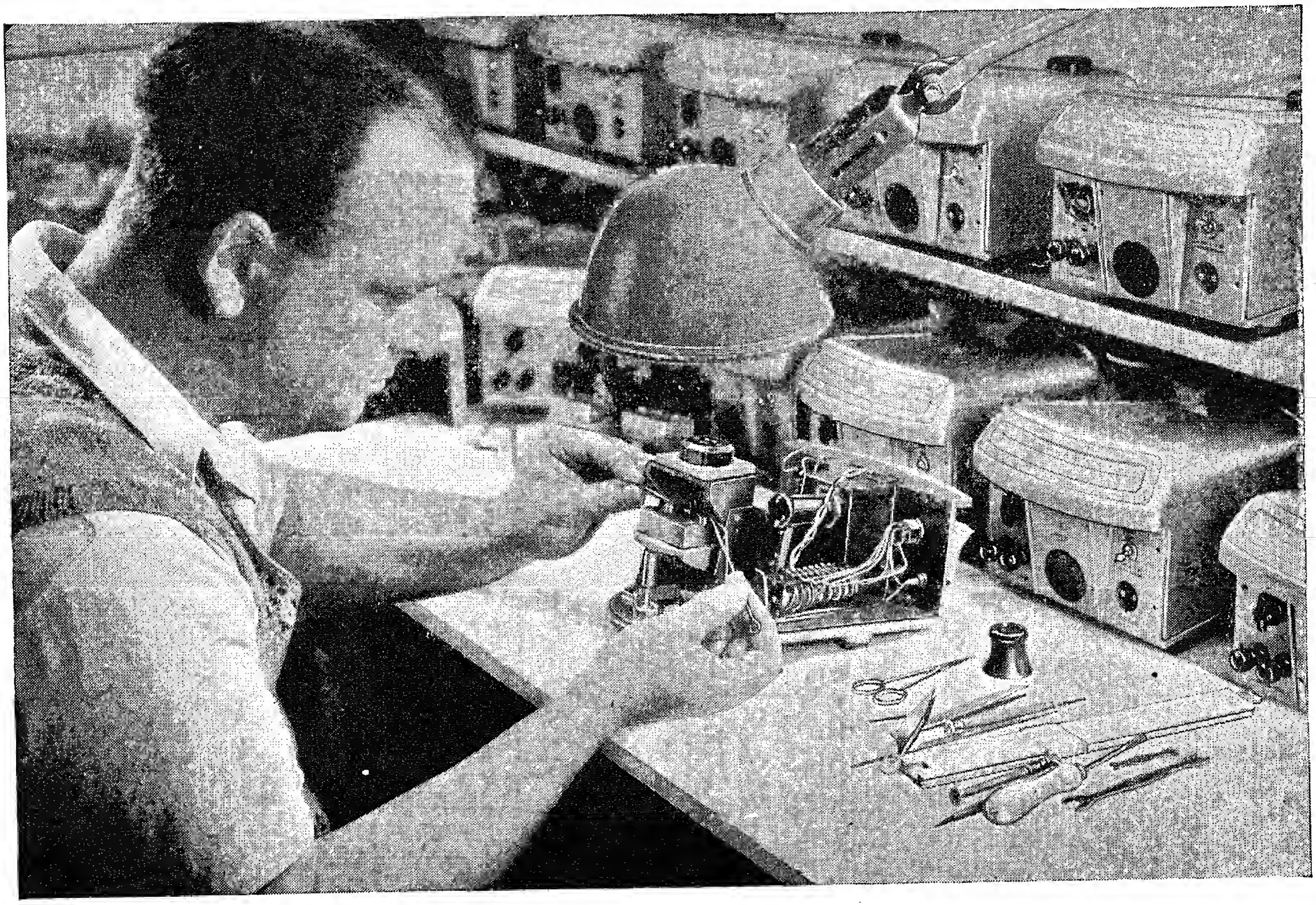

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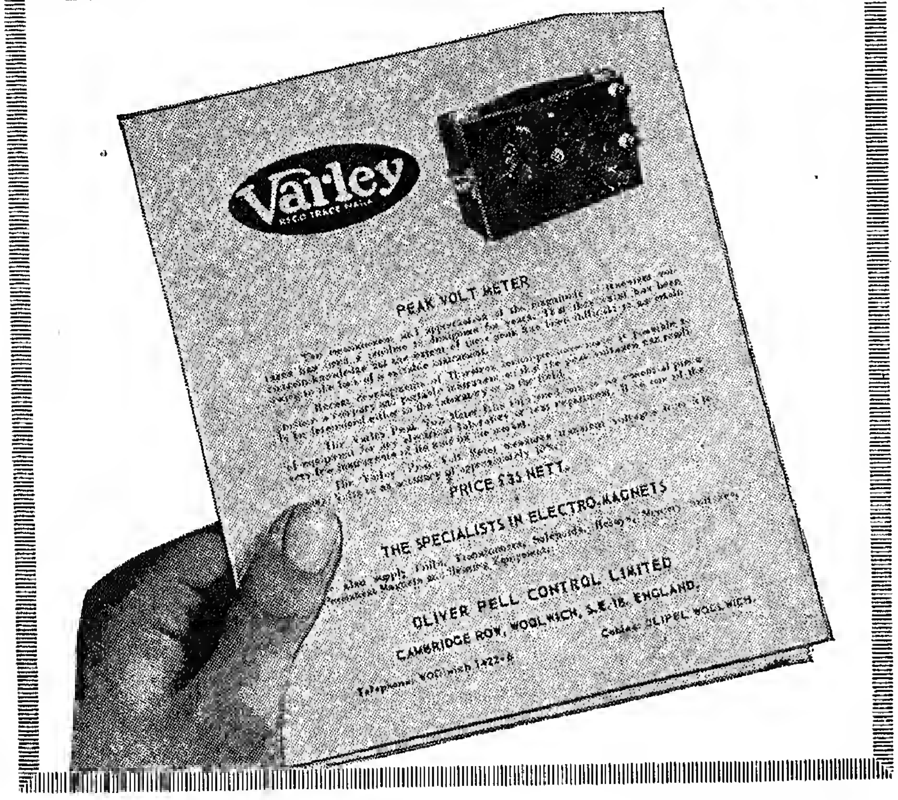

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THE PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

VOL. 102. PART A. No. 4. AUGUST 1955

621.3 : 629.12

Paper No. 1868
Aug. 1955

THE UTILIZATION OF ELECTRICITY IN SHIPS

A Review of Progress.

By G. O. WATSON, Member.

Some fifteen years, which include practically the whole of the war period, have elapsed since the last review on this subject,* and in the present statement it is hoped to include major trends and developments in the intervening years.

Radiocommunication, radar and kindred aids to navigation are excluded from the present review; space considerations will also preclude any detailed reference to electric propulsion or detailed technical consideration of any particular development.

(1) SAFETY OF LIFE AT SEA

A milestone of particular note in the history of marine applications was passed in 1948. In that year the International Conference on Safety of Life at Sea[1] met in London, and, having now been ratified by the requisite number of national Governments, its provisions came into operation as an International Code on the 19th November, 1952.

The Code is important from the electrical standpoint in that, whereas the 1929 Convention which it supersedes did not contain any electrical provisions, the 1948 Convention, Chapter II, Part C, is devoted entirely to this subject, and matters of electrical interest also appear elsewhere in the Code.

It will be sufficient to refer to some of the outstanding provisions, which, incidentally, apply only to passenger ships unless otherwise specifically mentioned. A new requirement for such ships is that they must carry an emergency battery which will come into service automatically in the event of failure of the main lighting supply. It must have sufficient capacity to supply emergency lighting for 30 minutes and to close the watertight doors. After that period the supply is taken over by an emergency generator or by a larger battery adequate for a period of 36 hours.

Other safety measures deal with the size and number of main generators, steering-gear supply, earthing of exposed metal parts, arrangement of cable ducts and distribution systems in fire zones, and the usual familiar safety clauses expressed in general terms.

In order to restrict the spread and magnitude of fire, ventilating fans must be provided with means for stopping them from two widely separated control stations outside the space concerned.

* *Journal I.E.E.*, 1940, 86, p. 203.

Mr. Watson is with Lloyd's Register of Shipping.

Electric radiators of the exposed-element type are not permitted. What is meant by "exposed element" (which is capable of a variety of interpretations) is not clearly stated, but in Statutory Instrument, 1952, No. 1948, issued by the Minister of Transport it is interpreted as "so exposed that clothing, curtains or similar material can be scorched or set on fire by heat from the element."

The 1948 Convention was ratified in the United Kingdom in the Merchant Shipping (Safety Convention) Act, 1949, and is interpreted by the Ministry of Transport in the form of Statutory Instruments, 1952, Nos. 1948 to 1959.[2] No. 1948 contains the electrical requirements and Clause 34(2) therein requires compliance with the relevant provisions of The Institution's Regulations for the Electrical Equipment of Ships.

The Ministry of Transport will publish shortly their Instructions to Surveyors amplifying in greater detail their interpretation of the requirements.

(2) RULES AND REGULATIONS

The Third Edition of The Institution's Regulations for the Electrical Equipment of Ships was published just prior to the period under review and has successfully stood the test of time. The Supplement which was issued in November, 1947, deals mainly with new types of cable now available.

The International Electrotechnical Commission resumed activities in 1948 on a Code for Electrical Installations in Ships, and a very comprehensive draft has been prepared. It was with the knowledge that this work was contemplated that the 1948 International Conference on Safety of Life at Sea decided to confine its requirements to points of principle and to omit precise details of construction. At the Philadelphia meetings of the I.E.C. in 1954 decisions were reached which will enable a final draft to be prepared which it is hoped will receive approval in time for publication in 1956. It is also intended to proceed shortly with preparations for a Fourth Edition of The Institution's Regulations.

(3) ALTERNATING CURRENT

Prior to 1939 the use of alternating current for auxiliary purposes was negligible, d.c. systems being practically universal. The United States had already adopted alternating current for

tankers, a policy which was continued during the recent war on the Type T.2 tanker.

Whether alternating current could be adopted more universally continues to be a topic of discussion in marine circles, and many papers and articles have been written around the subject. The key problems would appear to lie mainly in considerations of capital cost and the question of the electric winch.

On the score of reliability and cost of maintenance it appears to be fairly generally accepted that alternating current has advantages. On the question of cost the fact that, except for tankers, no full-scale installations have been made in the United Kingdom means that there has been no opportunity to assess costs from practical experience. This, however, is not the case abroad, and several articles have been published based on actual experience from which the conclusion is drawn that, in the cases cited, conditions favour alternating current. At least one foreign yard, with a very large output, will in future install only alternating current except where the owner specifically asks for direct current.

The real obstacle to greater use of alternating current lies mainly in the cargo winch and to a lesser degree in other services requiring variable speeds, such as the windlass, capstan, boiler fans and circulating-water pumps. The winch presents the most obstinate problem, forming, on account of the number required to work simultaneously, an appreciable load and a considerable capital cost. They not only require a very wide speed range, varying with the load to be lifted, but also demand a high light-hook speed. D.C. winches fulfil the requirements admirably, but the cost of an a.c./d.c. convertor is generally sufficient to rule out a.c. generation and distribution. Many attempts have been made to solve the winch problem, but although technically the requirements have been met, the cost has so far been too high. Where winches are not involved, as in tankers, a.c. systems have now become practically standard.

The question of frequency has received some consideration, and there are pertinent reasons for adopting 60 c/s as a standard. It is generally recognized that industrial-type motors are not particularly suitable for marine applications and that a special design of machine is necessary, and there is therefore no very strong reason for following land practice. In favour of 60 c/s it can be said that synchronous speeds are more akin to those at present in use with direct current and that when taking shore supplies a 60 c/s motor will be more suitable for running from 50 c/s than the reverse.

The problems to be met in designing an installation, while in many respects common to those of land installations, are nevertheless influenced by the comparatively small capacity of generating plant. Consequently voltage dip when using direct-on-line starting becomes a limiting factor in many cases. The effect of reduction of voltage on fluorescent lighting when a large motor is being started is only one of the problems.

It will be seen, therefore, that automatic voltage regulators ensuring a quick response and a design of alternators which will keep the voltage dip within reasonable limits are of prime importance. As practical examples of what has been achieved in this direction might be quoted a 700 kVA set carrying a steady load of 450 kVA at 0·8 power factor, which gave a voltage dip of 8·0%, recovering to normal in about 2 seconds when a load of 347 kVA at 0·13 power factor was added. In another case a 600 kW set on to which a load corresponding to 50% of its rated kVA was switched resulted in a voltage dip of 9·7% which was restored to normal range within 30 cycles. It is not uncommon in these equipments to start motors up to 25% of the generator rating by direct switching.

The largest a.c. equipment so far built in European yards is the S.S. *Christoforo Colombo* having a total installed power of 8 000 kVA, and a passenger liner at present building in the United Kingdom has approximately 4 160 kW at 440 volts.

Owing to the desirability of reducing risk of fire to a minimum, the use of oil-filled transformers and switchgear is avoided wherever possible, and in this respect a type of transformer filled with quartz sand which has been developed on the Continent has certain advantages.

Hitherto, with direct current at a maximum of 220 volts, the isolation and duplication of busbars has not been necessary for maintenance purposes, but with alternating current at 440 volts considerations of safety arise and there is a trend towards draw-out gear. It has to be remembered that once a ship is commissioned the busbars are practically never dead. Even when the generators are not running the bars are connected to a shore supply.

As already indicated, services requiring variable speeds for certain purposes cannot be dispensed with, and change-pole motors are commonly used. In the case of warping winches and anchor windlasses the requirements have been met in this way, the slack being taken up rapidly at the higher speed, and when the tension in the warping line exceeds a predetermined value the motor automatically transfers to the lower speed. Further increase in tension causes the automatic insertion of resistance in the stator circuit to hold the torque at a value which can be maintained for a short time. For the windlass the lower speed is required for loosening the anchor and the higher when the anchor is moving freely in water.

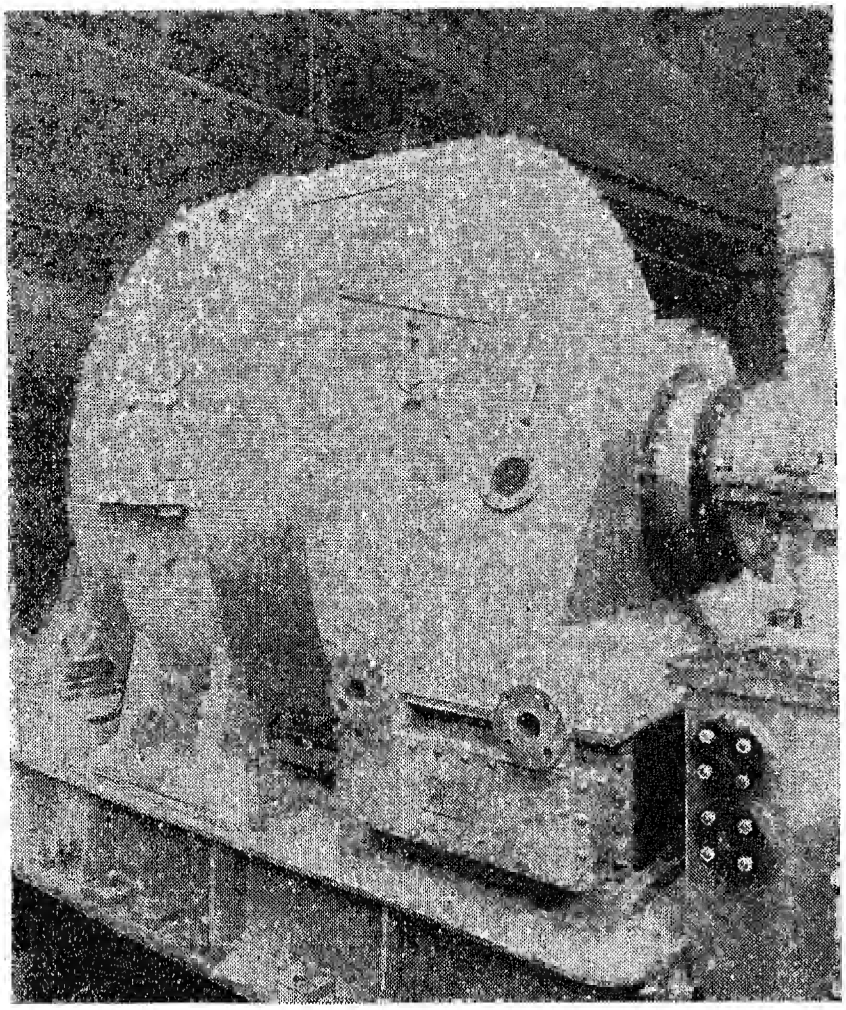
An incidental advantage accruing from the use of alternating current which all cross-Channel voyagers will appreciate is the possibility of using silent switches which eliminate the irritating noise inseparable from quick-make-and-break d.c. switches mounted on cabin panelling.

(4) GENERATORS

A study of environmental conditions in engine rooms has been undertaken by the British Shipbuilding Research Association with a view to improving the comfort of those who must perforce endure these conditions.

Generators and motors undoubtedly contribute a fair quota of heated air to engine rooms, thus not only raising the ambient air temperature but also at the same time affecting their own permissible temperature rise. An important contribution towards the solution of this problem is the development of a generator having a closed air-circuit embracing the whole machine with the exception of the commutator and brushgear. By means of a heat exchanger situated at base-plate level and cooled by sea water, the heat losses are carried away and not passed into the engine room; ventilating trunking is also eliminated (see Fig. 1). The usual objection to totally-enclosed machines, i.e. the accumulation of carbon dust, is avoided by keeping the commutator and brushgear outside the enclosure and at the same time making them accessible for maintenance and adjustment. A fan at the coupling end draws air through the cooler, which is mounted between the generator and the engine. One of the first vessels to be fitted with generators of this type was the S.S. *Himalaya*, the turbo generators being rated at 850 kW. Hitherto, totally-enclosed generators have usually included the commutator, with the disadvantage stated.

A development much favoured on the Continent makes use of generators coupled, usually through fluid couplings, to the propeller shaft, thus taking advantage of the better thermal efficiency of the main engine. The capital cost will, of course, be increased as the usual auxiliary generators are still necessary for service at reduced propeller speeds. Outstanding examples



[British Thomson-Houston Co., Ltd.

Fig. 1.—An 850 kW closed-air-circuit generator with heat exchanger mounted on the base-plate.

of this practice are to be found in the twin-screw tankers M.V. *Berenice* and M.V. *Bethsabee*, each having two 500 kW alternators chain driven through Vulcan oil couplings. Normal speed is 121 r.p.m., and when the speed falls below 98 r.p.m. each alternator is automatically cut out and the load is taken over by turbo-alternators supplied from a waste-heat boiler. Auxiliaries requiring a constant-frequency supply take power from a separate Diesel set.

(5) SLIP COUPLINGS

Slip couplings first came into general use about 1935, mainly in Sweden and the United States, but latterly in the United Kingdom. They consist of a squirrel-cage winding on one half of the coupling and a d.c.-excited salient-pole system on the other half, and are used to couple Diesel engines to gears for driving propeller shafts. Inserted between the engine and the gear box, they isolate the torsional oscillations of the engine from the gear teeth (see Figs. 2 and 3). Usually two or more Diesels are coupled to pinions engaged with a common gear-wheel, and arrangements can be made so that during manoeuvring two engines run in opposite directions and the propeller direction required is obtained by coupling-in the appropriate engine. The most powerful coupling so far built is of British manufacture and is rated at 5 650 b.h.p. at 228 r.p.m.

A novel development of this coupling is incorporated in a self-unloading cement carrier. Powered by two 640 h.p. engines, these are used for propulsion purposes through the slip couplings in the normal way, but when in harbour they can be used to provide 600 kW for cargo handling. Each engine shaft carries the d.c.-excited portion of the coupling, while the other half of the coupling, instead of having a squirrel-cage winding, carries a 3-phase stator winding. When at sea the 3-phase winding is short-circuited and the combined unit behaves as a slip coupling in the normal manner. In harbour, on the other hand, the propeller shaft is locked, the short-circuiting bars are removed

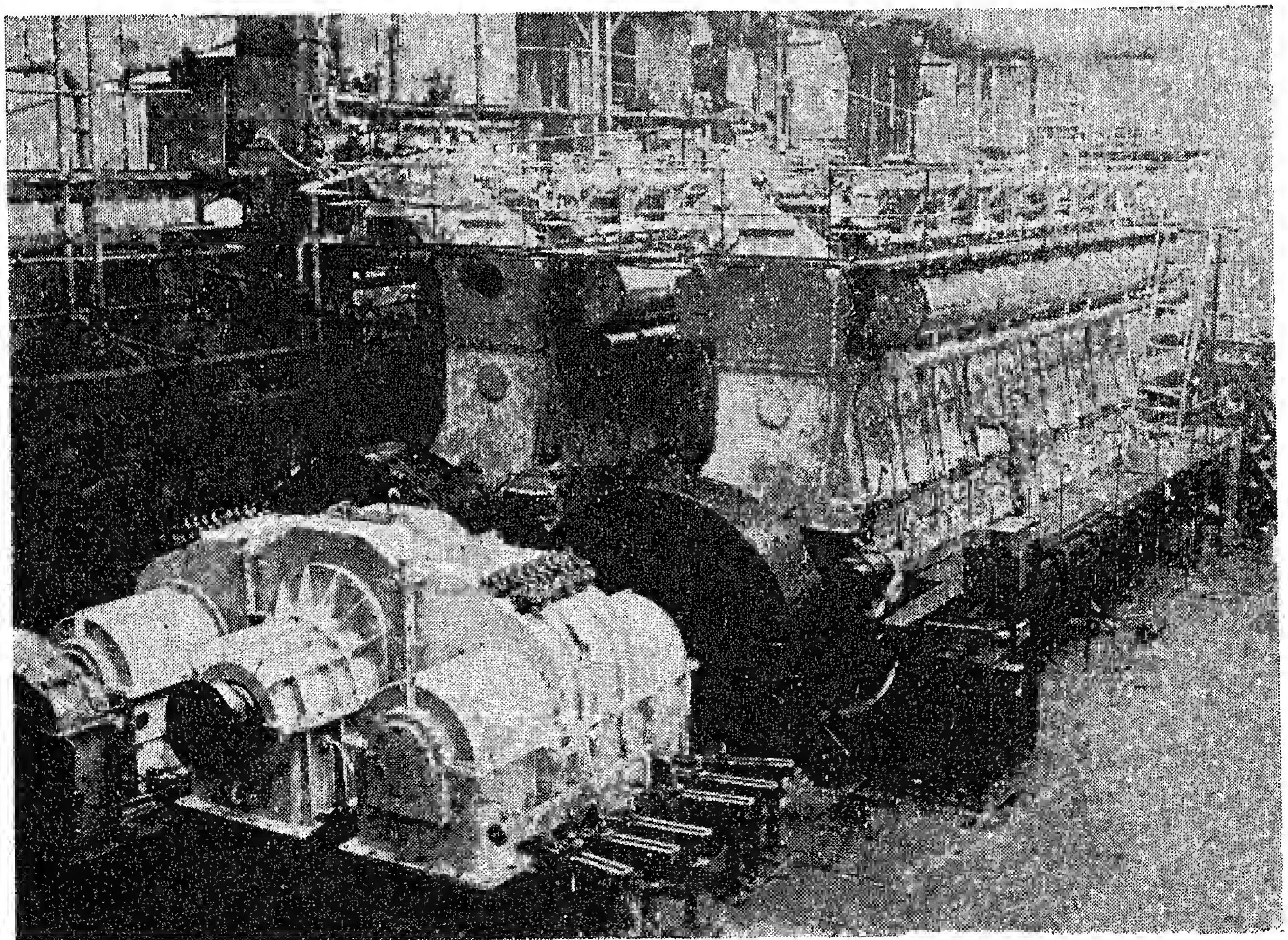


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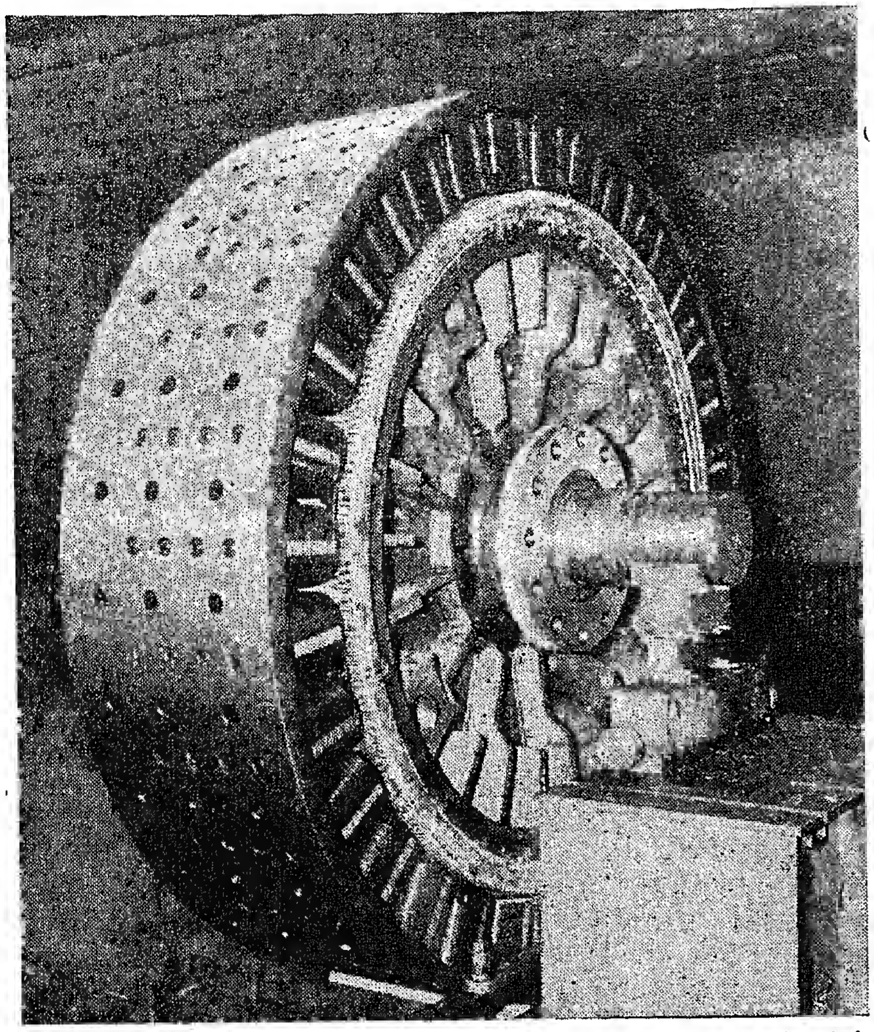
Fig. 2.—Two nine-cylinder engines, each of 4 500 h.p. at 225 r.p.m., coupled through slip couplings to a twin-pinion gear box.



[British Thomson-Houston Co., Ltd.

Fig. 3.—One of the electromagnetic slip couplings illustrated in Fig. 2.

from the a.c. winding, the 3-phase connections are coupled up and a 3-phase supply is available. The engines under these conditions are speeded up from the normal 250 r.p.m. for propulsion to 300 r.p.m., each being rated at 400 kW, thus making a total of 800 kW available.

(6) ELECTRONICS

As on land, the use of electronics in ships is extending, and this trend brings with it other problems and considerations. For instance, electricians are not carried in all ships, and if an electrical device fails it is the lot of the marine engineer to give the necessary attention. Whereas he is usually capable of dealing with relatively simple and straightforward power plant, electronic equipment is an entirely different matter. While there may be a radio officer on board, he is not an electrical engineer nor is he expected to function outside his own domain.

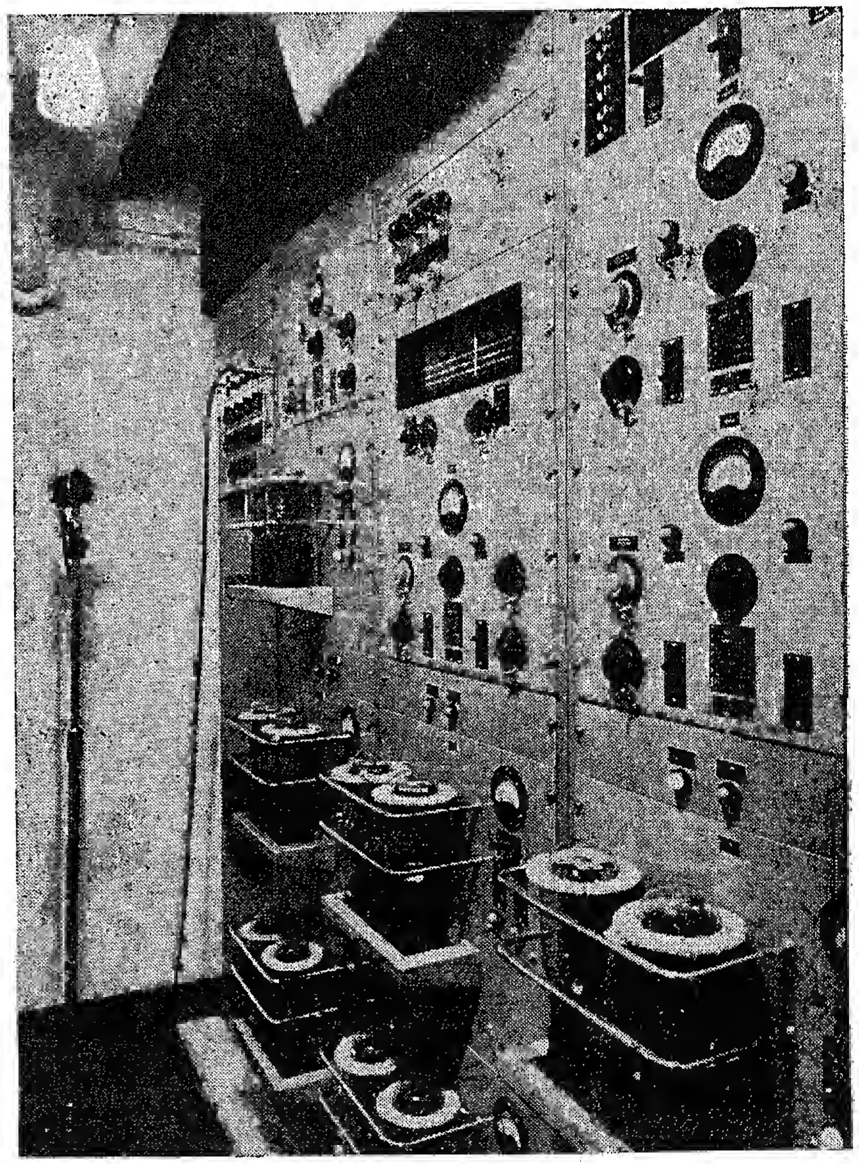
Another consideration is that of the reliability and life of electronic gear. During the time a ship is at sea most of its services will be in continuous day and night operation, and at the same time subject to conditions of shock and vibration. Normally it is not unusual for a ship to be at sea for 300 days in a year, which would be equivalent to 7 200 hours. A life of 100 000 hours will therefore give service for about 14 years, or about half the average life of a ship, and 1 000 hours would give service for only about 6 weeks. The gradual loss of vacuum or the evolution of gases from metal parts, on the one hand, or the absorption of gases by other surfaces are all factors affecting the life of a valve. All electronic gear, including resistors, capacitors, chokes, transformers, valves, rectifiers, etc., should therefore be designed for trouble-free and reliable operation over very long periods. Many of the services using electronic gear are of vital importance such as to warrant the manufacture of components of a higher standard of reliability and having a longer life than that usually associated with such apparatus. As an example of what can be accomplished in this direction, the special type of capacitor described in B.S. 1597 for interference suppression is estimated to provide a component of a much higher standard than those normally used in electronic circuits.

It is also satisfactory to note that considerable attention is being given to these factors in order to meet Service requirements, a factor which will ultimately benefit industrial users. What is important, however, is that designers and manufacturers marketing apparatus for use on applications of vital importance should incorporate components which will offer long life and reliability even if it results in increased cost. Short-lived and unreliable gear does harm to progress in this direction in the long run, and from the point of view of the user it is false economy any way.

Monitoring systems and standby equipment which can be quickly interchanged would be warranted in very vital applications.

Some of the uses to which electronics have been applied are in the control circuits of electric propulsion schemes and electromagnetic slip couplings, control of fan motors for air conditioning, oily water separators, voltage regulators, fire alarm systems, door control ("electric eye") and many other devices. A brief description of one of these may be of interest.

The question of oil pollution of the high seas has recently been the subject of an International Convention, and oily-water separators have an important function to perform. Oil-con-



[The General Electric Co., Ltd.

Fig. 4.—Main amplifier racks of a sound equipment system for 120 loudspeakers.

taminated water, before being pumped overboard, is first passed through a separating plant. The control system is based on the fact that substances have capacitance and the difference between the capacitances of water and of oil passing between suitable probes or electrodes and acting on electronic circuits enables an automatic control system to be operated.

Public-address systems on a typical large modern liner may comprise as many as 120 loudspeakers (Fig. 4). The arrangements may incorporate a priority system for the captain's announcements, with second priority for the purser. Use of the system is also made for the broadcasting of radio programmes, music from the ship's orchestra and gramophone records or by microphone.

(7) RADIO INTERFERENCE

An important contribution to the solution of the problems associated with the abatement of radio interference was contained in B.S. 1597: 1949. It presents the work of a representative committee which studied the problem over a period of 10 years, and there is no doubt that experience gained during the war years, when radiocommunication became a vital factor, contributed very largely to the final conclusions.

The problem was tackled on a very broad basis, and very wisely the responsibility for action is spread over all the interests concerned. Thus the supplier of the radio equipment, the shipbuilder and the electrical contractor are each in their separate spheres called upon to adopt measures to restrict interference. This represented to a certain degree a modification of earlier notions which were directed mainly towards the fitting of suppressors to practically every motor in the ship. In the final solution the screening effects of steel bulkheads and decks is recognized and efforts are concentrated on screening the radio cabin and fitting suppressors to all electrical services entering therein.

Coupled with these requirements is a section requiring a special construction of capacitors used as suppression components. Failure of a capacitor might in some circumstances involve the machine or equipment with which it was associated, and this specification aims at maximum reliability and long life.

(8) CABLES

The period under review has witnessed many interesting developments in regard to cables.

During the war, rubber shortages led to the recognition of p.v.c. by Lloyd's Register, but this has since been withdrawn owing to the inherent disability arising from its thermoplastic properties. In the confined spaces of a ship it is almost impossible to ensure that cables will not come in contact with steam pipes and other hot objects. Even if this is avoided in a new ship there is no guarantee against subsequent additions and alterations.

Shortage of lead resulted in the standardization of a polychloroprene (Neoprene) sheathed cable. Mineral-insulated cables have also made their entry into this field, and although progress has been slow they are now used extensively in boiler rooms and galleys where extreme conditions of heat must be catered for; with the latest type of cold seal the earlier difficulties and hazards of sealing have been overcome.

An important development of more recent origin has been the decision to make slight reductions in the thickness of rubber insulation and lead sheaths in line with similar changes in the Standards for land cables. Coupled with this decision, the manufacturing tolerances have been considerably tightened.

The 1947 Supplement to The Institution's Regulations initiated the re-rating of varnished-cambric-insulated and paper-insulated cables based on 104° F ambient air temperature as against 120° F in the third edition of the Regulations, thus permitting an appreciable increase in current ratings with corresponding economies.

(9) FUSES

The prejudice against the cartridge fuse on the score of cost of replacements is gradually disappearing, possibly influenced by the requirements of Lloyd's Register of Shipping, which insists on fuses having a category of duty commensurate with the prospective current. This means Category 3 in many cases, and very few rewireable fuses are to be found in this category. The United Kingdom is practically the only country where rewireable fuses still prevail. In some countries, notably Italy, there is a decided preference for the miniature circuit-breaker in place of fuses for distribution circuits.

(10) ELECTRIC PROPULSION

Space will not permit more than a brief reference to electric propulsion. No radical technical developments have taken place in the field of turbo-electric applications except that in the United States control of synchronous-motor installations from the bridge has now been achieved. It is also noteworthy that during the recent war approximately 480 tankers known as the T.2 type, each with a 6000 h.p. propeller motor, were built.

In Diesel-electric installations, although some notable a.c. systems have been built, it is more usual to use direct current. In this country it has become almost standard practice to adopt what is described as a controlled-current system. This is virtually a constant-current system, but may have different currents for different speeds. This is accomplished either by an exciter having three field windings, i.e. a self-excited, a separately-excited and a series winding, or through the medium of a rotating amplifier (i.e. Amplidyne, Metadyne, Magnavolt, etc.). Such systems lend themselves to control from the bridge, involving as they do the handling of small currents and being practically foolproof in operation.

(11) REFRIGERATION

The most notable development in the field of refrigeration is that of the electrical distance thermometers. Until recent years electrical thermometers were not acceptable to Lloyd's Register of Shipping as an alternative to bulb thermometers, as experience had shown that the degree of accuracy and dependability required under arduous service conditions was not obtainable. Reliability is of prime importance, as valuable cargoes of certain types are liable to be lost if the temperature is not controlled within narrow limits. Electrical thermometers are now obtainable having graduations sufficiently spaced and suitable sensitivity to render possible readings of $0 \cdot 1°$ F without difficulty on a moving ship over a range of approximately $-5°$ F to $+60°$ F. An accuracy within $\pm 0 \cdot 1°$ F at the freezing point of water under working conditions is attainable.

The arrangements of cargo holds and methods of cooling have undergone changes now necessitating in many cases a large number of small fans circulating air over batteries of brine-cooled pipes. Under this system, typical refrigerating installations would comprise from 20 to 40 fan motors of from 1 to 10 h.p. Lubrication is an important consideration, as the fans are usually in the air stream and the bearings are therefore subject to the cooling effect of the circulating air. When cargoes are loaded in the tropics the temperature will be fairly high, subsequently cooling to freezing temperatures, and the grease selected must be suitable for this temperature range.

An installation of novel character consists in the adoption of a 100 c/s supply for the fan motors, the number of fans involved being 76. Two running speeds are necessary, a high

speed during the initial cooling-down period and when passing through the tropics and lower speeds subsequently. A top speed of about 2 900 r.p.m. and a second speed around 2 000 r.p.m. are desirable. The latter is not obtainable with the usual 50 c/s, but with 100 c/s, 4-, 6- and 8-pole windings permit speeds of 2 930, 1 950 and 1 450 r.p.m. Absence of the commutator, which is at a disadvantage when working in refrigerated atmospheres subject to damp and condensation, coupled with inaccessibility for maintenance when installed in ducts, makes the squirrel-cage motor preferable for this application.

Where refrigerated spaces are separated by a steel deck or bulkhead, adjoining spaces are subject to a cooling effect due to conduction, leading to excessive condensation in this region, which, always undesirable, may be particularly so in certain circumstances. To counteract this action, local injection of heat is being tried in the form of mineral-insulated metal-sheathed heating cables clamped to the decks and embedded in the deck covering.

(12) LIGHTING

The main development under this head has been a pronounced tendency towards brighter and better lighting, achieved very largely by the use of fluorescent lighting, both hot- and cold-cathode, with emphasis on the cold-cathode version because of greater adaptability and compliance with decorative requirements. It is now common practice to find values of 12–15 lumens/ft^2 in the public rooms. The advantages of the cold-cathode tube may be summed up as follows:

(*a*) It has a long average life of 10 000 to 15 000 hours as compared with averages of 3 000 and 1 000 hours respectively for hot-cathode and tungsten.

(*b*) It can be obtained in a variety of shades so that colour distortion, so distressing in dining saloons, can be obviated, and on the other hand, novel effects can be produced in dance spaces, verandah cafés, etc., if desired. Reliable colour rendering in regard to food and ladies' make-up has been achieved by the blending of two or more colours in combination.

(*c*) It can be made to any shape desired by the architects and decorative contractors, and when used in cornices is shadowless.

(*d*) It has low heat dissipation, which is so desirable in the tropics; it also aids the air-conditioning plant and reduces its size.

As a typical example, the T.S.S. *Ocean Monarch* has a combination of cold-cathode fluorescent tubing and tungsten lighting, using more than half a mile of tubing and more than 1 000 tungsten lamps in public rooms. Power for the cathode lighting is taken from two 40 kVA motor-alternator sets fed from the d.c. mains, one constituting a standby set.

Since ship installations are still almost universally d.c., it is usually necessary to convert to a.c. when fluorescent lighting is used, whether hot- or cold-cathode. D.C. hot-cathode lighting is feasible, but the ballast resistance wattage is almost equal to the rating of the tube, and it is necessary to reverse the polarity periodically in order to overcome the darkening caused by the drift of mercury ions towards the cathode, particularly in the longer tubes.

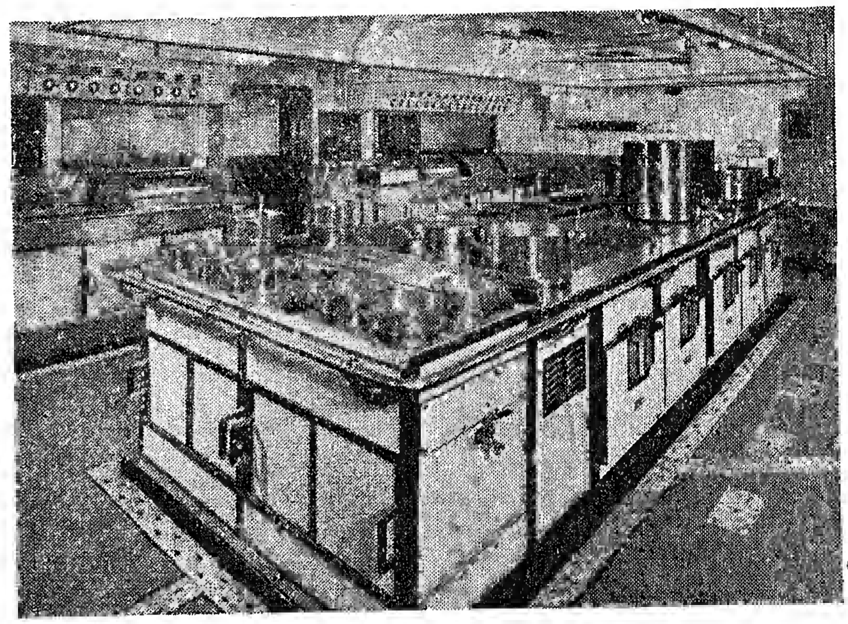
The better economy of the fluorescent lamp not only affects fuel consumption but may also affect the size of the generator. As an example of the saving, the same lumen output per foot run can be obtained with fluorescent lighting as compared with 25-watt lamps at 6 in centres for one quarter of the power. A factor in ship lighting installations is the low ceiling height, usually of the order of 7–8 ft.

For conversion from direct to alternating current, motor-alternator sets are preferred owing to the difficulty of independently controlling the voltage and frequency of rotary convertors. In the design of installations, service in the tropics requires to be taken into account as it will affect windings, fillings, etc., of components for both hot- and cold-cathode tubes.

(13) GALLEYS

The galleys and food-preparation rooms in modern passenger ships are now almost fully electric. In addition to extensive cooking equipment, hot cupboards, water boilers, fish fryers, baking ovens, etc., there are mixers, potato peelers, dough kneaders, slicers, etc., with separate galleys for passengers and crew.

Most galley installations follow orthodox lines, the range having drop-down oven doors and boiling-plates above the ovens. In most cases the control switches are separately mounted either on an adjoining bulkhead or suspended from the deckhead, thus keeping all connections and switches well away from the heat of the range (Fig. 5).



[*The General Electric Co., Ltd.*

Fig. 5.—Typical main-galley cooking equipment comprising a 10-oven island-type range with controls mounted on the deckhead.

The elements of boiling-plates are usually spirals embedded in a refractory in grooves on the underside of the plate, which results in an even distribution of heat over the plate surface. For roasting ovens and hot cupboards the elements are now mainly of the sheathed-wire pattern. The same method is used for water-boiler immersion elements.

The Admiralty led the way in the adoption of 440 volts 3-phase for cooking equipment, and this practice has now extended to merchant ships.

In some cases the roasting ovens are separate from the boiling-plates so that all cooking apparatus, including grillers, toasters and baking ovens, can be mounted at table height. Although this occupies a little more deck space it has proved very popular with the kitchen staffs.

There is an increased demand for a better external finish using light coloured enamel and stainless steel, which are easy to clean and give an improved appearance to galleys.

(14) CORROSION

The ever-present problem of corrosion continues to receive consideration, but research in recent years has received additional impetus, first because of increased activity in the carriage of petroleum and petroleum products, and secondly, because the hand-to-mouth methods of modern times do not allow any time for ship's plates to "weather" before use.

Wastage in cargo tanks carrying petroleum products shortens the life of tankers and is therefore a source of considerable financial loss which, from various causes, has materially increased in recent times. Various expedients have been tried, but cathodic protection appears at the moment to give

most promise. The corrosion which occurs is electrochemical as a result of differences of potential which occur on the surface of steel when in contact with an electrolyte such as sea water. The object of cathodic protection is to reverse the potentials of the galvanic cells by passing sufficient current through the water to the steel, thus converting the steel surface into a large cathode. This can be accomplished either by introducing additional material which electrochemically is anodic to steel or which can be made anodic by connecting to an external source of supply. However, corrosion is not confined to periods in ballast and occurs also when tanks are empty as a result of the use of sea water for cleaning and of condensation, so that cathodic protection is not the sole answer. There are other side effects which cannot be adequately dealt with here, and the whole problem has not yet been completely solved.

In tankers the impressed-voltage system is ruled out owing to the risk of explosion or fire, and full-scale experiments are therefore in progress on the alternative method. Anodes of zinc, aluminium and magnesium provide substantial differences in potential, magnesium having the largest and having the additional advantage of freedom from the tendency to form a scale, which occurs on the two other metals with consequent restriction of action. However, it has the disadvantage that it is consumed more rapidly and irregularly. The experiments now proceeding employ a special alloy containing a small percentage of aluminium and zinc. These are showing excellent results, but there is still room for improvement. As evidence[3] of the magnitude of the problem, it has been stated that the cost of renewals from this cause in a 12 000-ton deadweight ship after 12 years in the "white oil" trade might reach £250 000, and with demurrage of approximately four months the total might be £300 000.

(15) MISCELLANEOUS

The following are brief references to recent developments which it is not possible to deal with more fully.

A method of detection of leaks in the ferrules of condenser tubes consists in the introduction of small quantities of Fluorescene into the tube and the merest "weep" is shown up in the ultra-violet light of a black-glass lamp which is portable and mains operated.

It is now standard practice to use vertical-spindle motors and pumps, thus considerably reducing the demand on floor space.

Extensive telephone systems are now common, and in large passenger ships it is usual to find a telephone in each cabin. For instance, in the S.S. *Arcadia* and her sister ship *Iberia*, there is a 600-line manual and a 200-line automatic telephone system to provide service for passengers and administrative channels for officers and crew. Passengers can make service requests or can communicate with each other. Stewards' telephones have associated signal lamps which remain alight after the normal audible signal to warn the steward to call the operator on his return from other duties.

Fire alarm systems and patrol systems are also normal practice. From any of the established control points, telephone communication can be established with the officer of the watch.

In whale catchers, electrocution of the catch has proved successful. The harpoon is connected to the catcher by a trailing cable, and on striking the whale causes instant paralysis followed shortly by painless death. The weapon hitherto used consists of an explosive head harpoon. For humanitarian reasons it is hoped the electric system will be more widely adopted.

Plural-start systems in which a large number of motors are coupled to one starting panel, all being started by a common starter as required by pushbutton control, continue in demand. This system economizes space on the engine room floor and has been used to control as many as 40 motors ranging from the smallest sizes up to 250 h.p.

Except for a limited application of panel heating, space heating, where performed electrically, continues on the basis of convector-type heaters and low-temperature enclosed radiators.

Mechanical connectors in place of sweated thimbles have not yet made headway in this country, although they are now standard practice in the United States, where many excellent and reliable connectors are marketed. They usually require special tools and have to be of appropriate dimensions for each different size of conductor.

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Paper No. 1739 S
Dec. 1954

A CRITERION OF DISTRIBUTION COST

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(*The paper was first received* 30*th November*, 1953, *in revised form* 20*th July, and in final form* 1*st October*, 1954. *It was published in December*, 1954, *and was read before* THE INSTITUTION 3*rd February, the* SOUTHERN CENTRE *at* BRIGHTON 9*th February, the* MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL 7*th March, and the* SOUTHERN CENTRE *at* SOUTHAMPTON 23*rd March*, 1955.)

SUMMARY

The commercial performance of an Area Board can be judged by its success in keeping the distribution cost per kilowatt-hour down to the lowest possible figure. The absolute magnitude of this figure, however, depends on a number of factors which are largely outside the Board's control, such as the load factor and the sales per consumer. By making an appropriate adjustment for these factors, Boards can be compared on a uniform basis.

After the costs and revenues associated with auxiliary services have been deducted, the average costs of electricity supply in 1951–52 are related to kilowatt-hours, kilowatts of demand, number of consumers, etc., and expressed in pence per kilowatt-hour. The sum of these separate components minus the net deficit on the year's working equals the average price per kilowatt-hour throughout the country. A similar method is then applied to each separate Board's figures, using constants based on the average values for the whole country. The sum of these components plus or minus any net surplus or deficiency accounts approximately, but not precisely, for the mean revenue per kilowatt-hour of the Board in question. The differences (here called "discrepancies") disclose how far each Board's economy of operation departs from the average for the country, allowing for all the known functional variables. The figures can be used to compare the overall economies of the different Boards and to establish a form of target.

The results show that each Board's total cost can be accounted for on functional grounds to within a small percentage, and that the outstanding differences show a marked geographical distribution. In subsequent Sections the figures for 1952–53 and 1953–54 are presented, the year's changes are examined and the general conclusions are summarized.

(1) INTRODUCTION

(1.1) Basis of Measurement

In engineering, measurement is the essence of knowledge, and this principle is as true of the economic aspects as of the purely physical ones, although it is much more difficult to apply. Commercial efficiency cannot be measured, like power-station efficiency, to three significant figures, but its measurement is no less important, and one never really knows what is happening until it has been expressed in quantitative terms.

The chief difficulty in making comparisons of distribution economy is that of finding a suitable denominator. The only quantity known at all stages of the process from generation to sale is the kilowatt-hour, and costs per kilowatt-hour form the most convenient and often the only possible basis of assessment. Yet any broad comparison, e.g. between different Area Boards, of the distribution costs per kilowatt-hour yields results so erratic that they serve only to illustrate the uselessness of such a basis unless heavily qualified in various directions. This is not surprising, since considerably less than one-half of the total costs of electricity supply and only a very small fraction of the distribution costs are directly energy-related. Without quoting figures it is quite obvious that the cost of supplying 1 kWh will be much less if each consumer takes 1 000 kWh a year than if he takes only 100 kWh. Its cost will be less if the kilowatt-hours are taken steadily than if they are taken in sharp peaks, and will generally be less if many are taken per square mile rather than few. It will also be less if the kilowatt-hours are not encumbered by reactive consumption.

Attempts have sometimes been made to use the known kilowatt-hours data in some other form, e.g. kilowatt-hours per pound of distribution capital.* The more usual way out of the difficulty is to disregard kilowatt-hours altogether, except for cost elements (like fuel and losses) which are directly energy-related, and to use other bases such as kilowatts or kilovolt-amperes of demand, number of consumers, area served, etc., for the remaining costs. While such a functional treatment forms the only possible scientific basis for a cost analysis, it does not furnish a simple or convenient criterion for comparisons of distribution economy.

(1.2) Weighted Kilowatt-Hour Costs

The paper uses this generally accepted functional cost analysis, but builds up from these three or four components a single cost criterion which can be used as a simple yardstick for comparing distribution economics. The criterion will necessarily be in the form of a cost per kilowatt-hour, but will be weighted so as to allow for the other main cost variables. In other words, all the costs will be loaded on to the kilowatt-hours by means of appropriate multiplying factors.

A simple numerical example of this weighting will serve to illustrate the matter. In weighting for load factor, if the costs at a certain point are represented by £5 per annum per kilowatt plus 0·5d. per kilowatt-hour, it is clear that load factors of 20 and 40% will result in demand costs of approximately 0·68 and 0·34d./kWh respectively. After the addition of 0·5d., the overall figures of 1·18d. and 0·84d. may then be regarded as kilowatt-hour costs weighted to allow for the fact that each kilowatt-hour has twice as many demand kilowatts associated with it in the first case as in the second. Such a calculation is normal practice, of course, although it is not usually expressed quite in this way.

The same principle can be applied to consumer costs. If the average consumer in a certain group costs the undertaking £2 per annum, additional to all the costs related to kilowatt-hours and demand kilowatts, the consumer with a yearly consumption of 1 000 kWh will incur an additional cost of approximately 0·5d./kWh, but one with a consumption of 10 000 kWh per annum will incur only one-tenth as much, i.e. 0·05d./kWh. The cost per kilowatt-hour can thus be weighted by a component representing an appropriate share of consumer costs.

In short, the distribution of a given number of kilowatt-hours per year in a particular area is associated with a certain number of demand kilowatts and a certain number of consumers, and the corresponding costs can be expressed as an element in the overall cost per kilowatt-hour. Differences in the size of the area covered by the distribution or in the power factor of the supply can also be compensated for in a similar manner if

Mr. Bolton is with the Central Electricity Authority.

* KENNEDY, J. M., and NOAKES, D. M: *Journal I.E.E.*, 1933, 73, p. 97

necessary; and provided that appropriate data and constants can be arrived at, there is no reason why this single yardstick should not take account of all the essential variations. This should serve both to compare the results of different Area Boards and to plot the progress of a given Board from year to year.

(1.3) Costing Stages

The process of arriving at a scientific cost statement involves three stages, namely

(a) *Cost classification*, i.e. the assembly and arrangement of cost items on an accountancy basis.

(b) *Cost relating* on a functional basis, i.e. expressing the cost per unit of service, such as the kilowatt-hour, demand kilowatt or kilovolt-ampere, number of consumers and area served.

(c) *Cost allocation*, i.e. sharing the costs between consumers deemed to be responsible.

The paper is concerned only with the second of these stages. While it will finally relate everything to kilowatt-hours, intermediate steps will make use of other quantities which are known for each of the separate Boards, such as kilowatts of demand at the bulk-supply points, magnitude of fixed assets, number of consumers and areas of supply. Briefly, the method is to use the individual Board's variations as a guide to a law for relating the capital expenditure, and then to analyse the combined accounts so as to establish appropriate relating constants. These constants are then applied to each Board's accounts in turn.

(1.4) Theory of Cost Relating

The services rendered by electricity supply may be likened to a rope made up of some four or five separate strands, namely the supply of energy, of maximum power, of reactive components and of individual consumer service. Where electricity supply is unique is that each of these separate services or elements of consumption is controlled by the consumer, whose demands of each kind vary. This variation has a corresponding effect on the cost of supply, since each service component has specific and identifiable costs attached to it. The supply of energy requires a strictly proportional expenditure on fuel, the meeting of demand entails capital charges on a corresponding amount of generating and other plant, and reactive consumption entails its quota of expenses, while other costs, e.g. for service connections and meters, are proportional to the number of consumers.

Electricity supply is possibly unique in that each component of the service is capable of fairly precise measurement at one or more points in the system, so that accurate costing, although complicated, is at least theoretically possible.

(1.5) Method of Cost-Relating

The principle of cost relating can be stated very simply. To find the cost per kilowatt-hour, per kilowatt of demand, per consumer, per mile of route, etc., one asks the question: if the kilowatt-hours (kilowatts, consumers, etc.) increased by one, without any increase in any of the other quantities, by how much would the total costs increase? The word "one" must obviously not be taken literally, or the answer will frequently be zero; except for a few specific items such as coal and service connections, the existing expenditure and equipment will usually cope with one additional unit without any increase whatsoever. The additional unit must therefore be regarded as typical of some hundreds or thousands of its fellows, or some costs will inevitably slip through the net. The aim to be kept continually in mind is that all outgoings are ultimately to be related to one or more of these service variables, on the assumption that when every element of the service is doubled (kilowatt-hours, kilowatts, consumers and area) the costs will have doubled. This point is elaborated in Section 3.4.

The connection between increase of service and increase of expenditure may be a very immediate one (as with kilowatt-hours and coal) or a very long-term one (as with kilowatts of demand and generating sets), but the connection must be held as inviolate if costing is to have any meaning. Just as in climbing a hill, it is the same in the long run whether one rises by infinite gradations, as on an inclined plane, or by a series of jerks, as on a stairway.

The above concept requires qualification where charges on capital assets are concerned, owing to changes in prices. The paper is intended to be a factual statement, not a prophecy; i.e. an allocation of past costs, not an estimate of future ones. The concept of one additional kilowatt, consumer, etc., is merely a convenient mental tool and must have regard for the fact that capital charges actually relate to assets which have been purchased over the preceding 30–40 years and at prices covering a range of 1–3 or more. Hence, in an assessment of, say, the consumer-related cost on the basis of "one additional consumer," the cost of the service connection must not be the present-day cost but the cost at the average price of all existing services.

(2) LAW OF CAPITAL ASSETS

(2.1) Graphical Approach

Apart from costs proportional to kilowatt-hours and therefore easy to relate, the largest group of costs is that of the capital charges on the fixed assets. The first step, then, is to establish a connection between investment on fixed assets and maximum demand and/or other variables. Fig. 1 shows the first cost of the

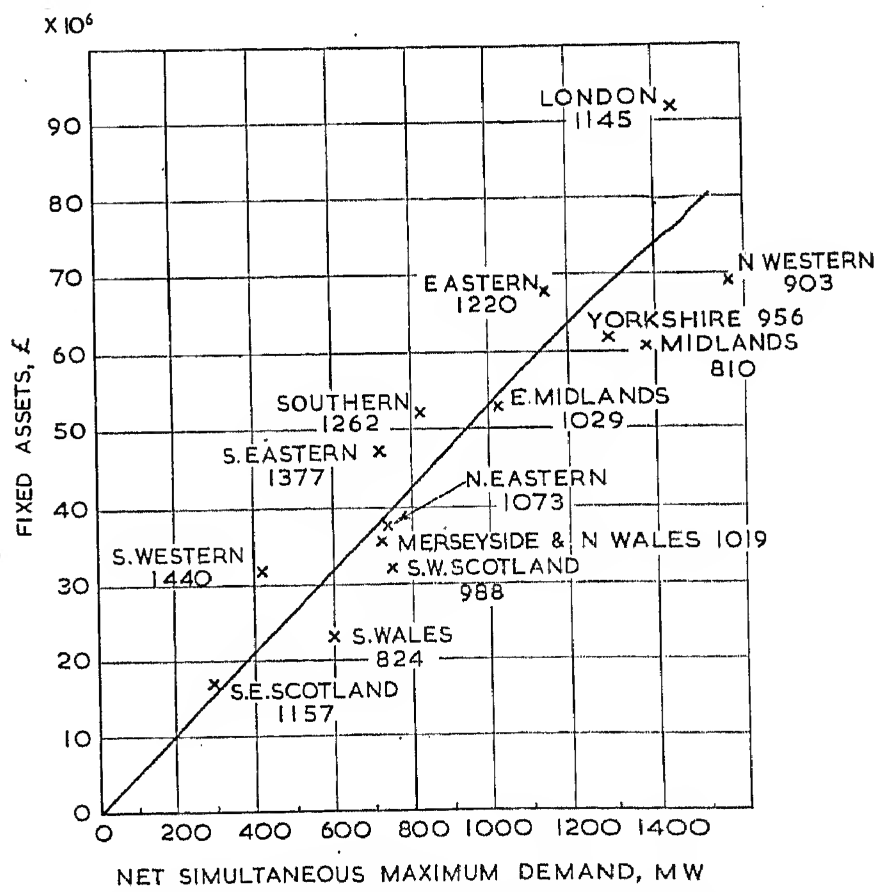

Fig. 1.—Fixed assets and maximum demand.

The numbers below the names of the Area Boards indicate the number of consumers per megawatt.

fixed assets of the fourteen Area Boards as at the 31st March, 1952, plotted against the net simultaneous maximum demand at the bulk-supply points. This latter figure is found from the maximum demand of the supplies purchased by the Boards from the Central Authority, plus that of any other bulk purchase, less bulk sales to other Boards. The total for the country is slightly greater than the total simultaneous maximum demand on the Authority's bulk-supply points. A straight line has been

drawn through the origin, and its slope represents the ratio between total capital expenditure and total demand.

It will be seen from the graph that there is a fairly close linear correlation between the points, but this is by no means perfect. One obvious reason for divergence is that a considerable amount of distribution capital expenditure is not a function of maximum demand, but is more closely related to the number of consumers. (A minor factor is that the maximum demand at the bulk-supply point is not necessarily in a uniform relationship to the demands on the various parts of the distribution system.) This *a priori* reasoning is confirmed by the details in Fig. 1. Under each Board's name is a figure giving the number of consumers per megawatt of bulk-supply demand. It will be found that, without exception, points lying above the line have higher figures than those below the line, indicating that wherever there was a high ratio of consumers to kilowatts the investment per kilowatt was above the average.

It might appear possible to apply the method of regression analysis in order to obtain a more exact solution. The equation is in the form of $y = ax_1 + bx_2$, where y is the total investment in pounds and x_1 and x_2 are the demand kilowatts and the number of consumers. The problem is to find values for the constants a and b which give the nearest fit, given the values of y, x_1 and x_2 for a number of individual cases. Unfortunately, 14 is too small a number to yield satisfactory results, particularly when x_1 and x_2 are varying fairly uniformly together and in the same sense. Moreover, it is evident from Fig. 1 that London is a special case, owing partly to the fact that site values in its area average several times higher than elsewhere in the country.

A semi-graphical method was therefore pursued, using 13 points only, i.e. omitting London. The method is based on the assumption that, while the investment clearly includes a consumer-related as well as a demand-related element, the latter predominates and can be treated as the major independent variable. Investments of £5, £10, £15, £20 and £25 per consumer were assumed in succession, and after subtracting these amounts the remaining figures were plotted to a base of maximum demand. The most successful of these, namely that in which £15 per

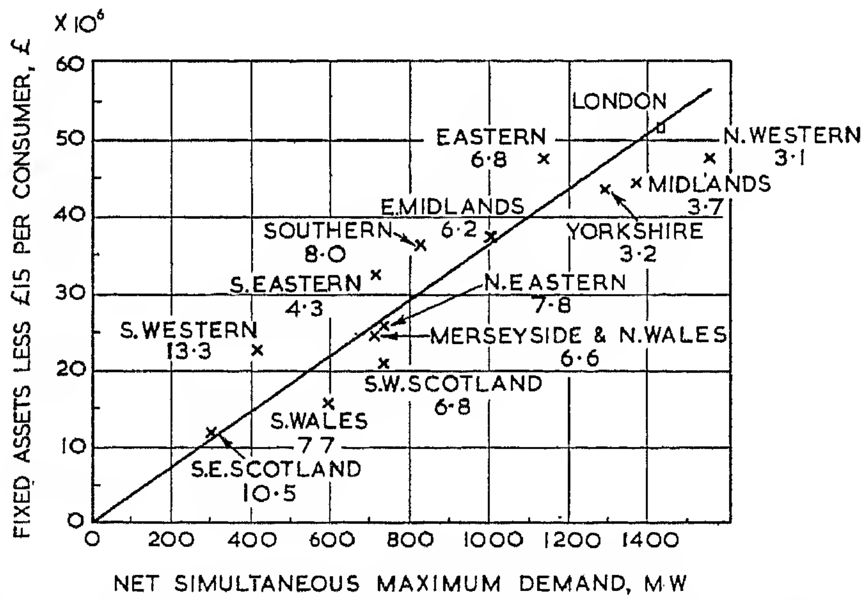

Fig. 2.—Fixed assets (less consumer allocation) and maximum demand.

The numbers below the names of the Area Boards indicate the area (square miles) per megawatt.

consumer was deducted, is shown in Fig. 2. (The curve with £20/consumer deduction was, however, not noticeably inferior.)

The results of this examination were not conclusive, for the reasons already given. Owing to the considerable correlation between x_1 and x_2 it is impossible to separate their coefficients with any confidence when so few values are available. Thus, while the graphical approach points clearly to the existence of a consumer component, it is inconclusive as to its magnitude unless a breakdown of the data (say to a sub-area level) is available.

(2.2) Numerical Analysis

A more direct approach to the problem is to estimate a figure from the segregated capital expenditure, which is given under a number of heads in the annual reports. Prior to Vesting Day the Electricity Commission's "expenditure charged to capital account" gave only a single total for mains and services. But since vesting, this expenditure has been divided under three heads, and for the present purpose it has been assumed that the existing ratio between them applies also to the pre-vesting expenditure. Table 1 is an attempt to divide these figures into consumer-related and demand-related groups.

Starting with the service connections and assuming (as is usually the case) that only a single cross-section is used for all the normal services, the whole of this expenditure can be regarded as consumer-related. With low-voltage mains, in an area not fully developed the mains extensions will to some extent be required on account of additional consumers and independently of any additional demand; but in a fully developed area, in which almost all potential consumers lie on the routes of existing mains, reinforcement of these mains will be determined only by load increases and not by consumer increases. Similar remarks apply to low-voltage substations, and frequently in a developing area the necessity for, though not the capacity of, a new substation will be the consequence of additional consumers. For the high-voltage section of the distribution system a very large proportion of the expenditure must be considered to be demand-related.

Certain of the expenditure on other than distribution plant, e.g. that on showrooms and service centres, will also have a

Table 1

First Cost of Fixed Assets as at the 31st March, 1952 [A.17]

Factor	First cost	Percentage of total	Allocation to consumers		
	£ × 10⁶	%	%	£ × 10⁶	£ per consumer
Overhead mains* ..	83·2	12·7	0	0	
Underground mains*	230·8	35·3	30	69·2	5·1
Services*	105·1	16·1	100	105·1	7·8
Land and buildings:					
Operational	31·5	4·8	20	6·3	
Offices and service centres	9·6	1·4	80	7·7	3·0
Plant and machinery ..	137·0	21·0	15	20·6	
Tools and instruments	1·5	0·2	15	0·2	
Office fittings, machinery and plant	5·0	0·8	80	4·0	
Vehicles	4·4	0·7	50	2·2	
Meters	45·5	7·0	100	45·5	3·4
Sub-total	653·6	100·0		260·8	19·3
Public lighting: apparatus on hire†	26·0				
	679·6				

* Assuming that the proportions of overhead, underground and services are the same before as after vesting.

† Excluded from this estimate on the grounds that these assets are largely employed in the activities whose revenues have subsequently been excluded.

considerable element of consumer-relation. After making the best possible allowance for these various factors, the percentages given in the third column of Table 1 were produced, on the assumption that the whole asset cost is to be related either to

consumers or to demand. The final result of the estimate is to give a figure of £19·3 per consumer. It will be appreciated that the most dubious element in the estimation is the allocation of mains, since this applies to a substantial body of expenditure. But even if the allocation were zero the total would still exceed £14 per consumer. (The references in square brackets in the Tables are to the B.E.A. Fourth Report and Accounts for 1951–52.)

(2.3) Conclusions regarding Consumer Element

It will be seen that the conclusions arrived at from these two methods of approach are in general agreement. Possibly the higher proportion of consumer cost (as represented by £20 per consumer in 1951–52 rather than £15) is a reflection of past conditions when many areas were still being electrified, and that a lower proportion is more appropriate to present-day conditions of development saturation. A figure of £15 per consumer has therefore been taken for the present purposes.*

Looking ahead, it might appear that the proportion of consumer-related capital will tend to decrease slightly and may in the future represent little more than the cost of service connections and meters. The absolute value will, of course, increase as the proportion of post-war investment increases, but this applies equally to the demand-related assets and does not necessarily affect the proportions. It need hardly be said that the present calculations relate only to historical costs; if one were dealing with marginal costs (in relation to new consumers or additional demand), both the per-consumer and the per-kilowatt figures would be much higher.

Once the decision regarding consumer element has been made, the remaining constants are determined, since the overall totals are known. Thus if b is 15, a must be about 36 in order to give the correct total for the 13 Boards; but since London has been omitted from this calculation it is necessary to bring it back into the picture, and this can be done by increasing each of the constants by 20% in the case of the London Board. (The figure of 20% is purely arbitrary and has been chosen because it brings the point approximately on to the line of average.)

Fig. 2 shows the value of the fixed assets less £15 per consumer to the same base as in Fig. 1, namely maximum simultaneous demand at the bulk-supply points. (The small square indicates the position of the London Board assets divided by 1·2.) The slope of the straight line represents the ratio of the overall totals with this adjustment, and it will be seen that the fit is demonstrably closer than that of Fig. 1.

(2.4) Effect of Area Served

The last service variable to be considered as affecting capital investment is that of distance or area covered. It is obvious that both the demand-related and the consumer-related costs will also be to some extent distance-related. Thus the cost of an overhead-line network (taken as 100% demand-related) will be closely dependent on the area served. A service-connection cost (taken as 100% consumer-related) will also be directly proportional to the distance from the mains. Similar remarks apply to costs having a joint relationship to demand and consumers. In most cost analyses, distance has to be averaged out, but this is unsatisfactory when comparing different areas, since there is likely to be a greater capital cost per kilowatt and per consumer in distributing over a dispersed low-density area. On the other hand, extremes sometimes meet, and when there is an exceptionally high density, as in London, unit costs may increase because of expensive site values.

* The element of consumer cost has so often been under-emphasized in the past that the author is anxious to avoid any charge of exaggerating its importance. Where any doubt exists, he has therefore tried to tilt the scales away from consumer costs, and this is one reason for his making a conservative estimate and taking £15 rather than £20 per consumer.

In Fig. 2 the figures under each Board's name give the area served (square miles) per megawatt of maximum demand (average, 6·8). If there is a size correlation one would expect to find that points whose areas per megawatt are higher than average would tend to lie above the line of best fit, and vice versa. Actually a number of the points do follow this rule, but a few follow the opposite rule, and the remainder show results of an indeterminate character. Evidently there is some correlation, but it is not sufficiently marked, nor is there a sufficiency of points to permit a mathematical treatment.

A similar assay was made in a curve plotting the total capital cost (i.e. consumer-related as well as demand-related), but the area correlation was then even less marked. This is perhaps not surprising, since the chief consumer-related capital cost is that of the service connections, and while this is a function of length, it is by no means certain that Boards with a big area per consumer necessarily have service connections longer than the average. In comparisons between Boards, distance is more likely to affect the mains than the services, and therefore chiefly to affect the demand-related expenditure.

After several attempts on these lines, the method finally adopted was to weight only the demand-related capital costs and to do this in proportion to the fourth root of the areas served. This is tantamount to saying that, if there were two areas with the same maximum demand, one of them occupying a square of twice the side or a circle of twice the diameter (i.e. four times the area) of the other, its demand-related costs could be expected to be 1·4 (i.e. $\sqrt{2}$) times those of the other. The method for calculating the different values was to divide each Board's demand-related assets costs by the fourth root of its area per megawatt of demand, and to multiply by a constant such that the sum of these adjusted costs equalled the actual total cost. London was omitted from this adjustment, since here the significance of area is if anything in the reverse direction.

The only justification for this treatment, apart from *a priori* arguments (which must always be viewed with a healthy suspicion), is that when plotted to a base of maximum demand (figure not shown) the deviations of the individual points from a mean line through the origin are materially less than that of the unadjusted points shown in Fig. 2. This area variation may appear surprisingly small, but attempts to use a more highly-geared adjustment such as the square root of the area per megawatt gave greater divergencies from a straight-line law.*

(2.5) Cost Formula

In its simplest form, and omitting the adjustment for load density, the equation for the fixed assets is very approximately £36 per kilowatt of bulk-supply demand plus £15 per consumer, with a 20% increase in the case of the London Board. In full, the results can be expressed algebraically as follows:

$$A = k_1 D + k_2 C$$

Where A = First cost of fixed assets at end of year, £.
D = Simultaneous maximum demand at bulk-supply points, kW.
C = Number of consumers.

The values of the constants are as follows:
k_2 = 18 for London; 15 for other Areas.
k_1 = 43·24 for London; 23·60 $\sqrt[4]{(\text{area/MW})}$ for all other Areas.

When this formula is applied to each Area in turn the total for A agrees with the actual total of fixed assets, namely £679·61 × 10^6.

* The optimum index appeared to be somewhere between the cube root and the fourth root.

(2.6) Effect of Load Character and Distribution Voltage

In comparisons between Boards having loads of widely different character there are obviously other capital-cost differences besides those so far taken into account. Thus one Board may have a bigger proportion of low-voltage sales and this will involve a disproportionate investment on low-voltage mains. If mains expenditure were divided between high- and low-voltage distribution, it would be possible to compensate directly for this variable. It is doubtful, however, whether the extra complication would be justified, and it seems preferable to regard this cost variation as being correlated to the consumer cost and as covered by the consumer-cost variation. Broadly speaking, low-voltage consumers are small consumers, and Boards with a high ratio of consumers to kilowatt-hours are likely to have a proportionally large expenditure on low-voltage networks. In other words, some of the capital costs which have been segregated above are what might be called "associated consumer costs."

(2.7) Effect of Power Factor

One service factor has been entirely omitted from this survey, namely that due to bad power-factors. Usually, undertakings not only supply energy consumption and power demand, but also supply reactive consumption and reactive demand where this component is needed to excite the field of induction motors and transformers. This chiefly complicates the demand-related distribution costs, which are usually more closely proportional to kilovolt-amperes than to kilowatts. (The reason for not using kilovolt-amperes from the start in the present instance is, of course, that the bulk-supply demands are known only in kilowatts.)

This factor could be fitted into the demand-related element of the criterion either from a knowledge of the power factors of the separate bulk supplies or by some comparison based on the ratio of industrial to non-industrial consumption in each area. This latter method, however, would bring other variables in its train, and in the paper power-factor differences have been neglected, any such adjustment being left for some later worker in the field.

(3) ANNUAL EXPENSES: RELATION TO OUTPUT

(3.1) Other Activities

Items 2–20 of Table 2 show the overall revenue and expenditure account for the 14 Area Boards for the year 1951–52. The first step is to "hive off" the activities other than those of electricity distribution. For this purpose it is assumed that the net revenue from the sale of electricity (i.e. electricity income less bulk purchases), minus the net loss on the year's operation, represents the true cost of electricity distribution (£84·76 × 10^6). This involves deducting a sum of £5·905 × 10^6 from the gross expenses (item 19) in order that the accounts shall continue to balance. The assumption underlying this deduction is that the cost of activities other than the sale of electricity just equals the non-electrical income.*

Some of the costs which should be deducted can be identified under the heading of consumer service [A. 8]. They comprise repairs and maintenance of hired equipment and public lighting, together with a *pro rata* share of transport and of the proportion of general charges. They total £4·813 × 10^6 (item 24) leaving a small unidentified residue (£1·092 × 10^6) still to be deducted (item 28), which is 1·272% of the total. It is reasonable to assume that these non-electrical activities involve a small call on all the Board's equipment and facilities, and a proportionate reduction of 1·272% is therefore made in each of the specified cost items (final column of items 21–27).

Table 2

AREA BOARDS COMBINED ACCOUNTS FOR 1951–52

Item			£ × 10^6	Source in Fourth Annual Report
1	Total fixed assets at the 31st March, 1952		679·607	A. 16
2	Income from sale of electricity		253·643	C. 1
3	Purchase of electricity		170·211	
4	Net income available for distribution		83·432	
5	Net deficit on year		1·333	
6	Assumed cost of electricity distribution		84·765	
	Statement of Costs			
7	Depreciation		22·485	C. 1, line 15
8	Interest and financing		11·080	Lines 23 and 24
9	Rents, insurances, etc.		1·023	Line 12
				Source in Fifth Annual Report
10	Distribution cost (operation, repairs and maintenance)		22·042	A. 3 and A. 7
11	Sub-total (items 7–10)		56·630	
12	Meter reading, etc.		7·959	A. 3 and A. 9
13	Consumer service		10·189	A. 3 and A. 8
14	Rates payments		7·054	C. 1, line 13
15	Administration and general ..		8·470	A. 10
16	Training, system changes, miscellaneous interest paid less that received		0·368	
17	Sub-total of common costs (items 14–16)		15·892	
18	Gross total (items 11, 12, 13 and 17)		90·670	
19	Less assumed cost of other activities		5·905	
20	Net total = assumed cost as item 6		84·765	
	Restatement of Costs			Costs less 1·272%
21	Sub-total related to assets (item 11)		56·630	55·910
22	Meter reading, etc. (item 12) ..	£ × 10^6	7·959	
23	Consumer service (item 13)	10·189		
24	Less cost attributable to other activities	4·813	5·376	
25	Sub-total related to consumers		13·335	13·165
26	Sub-total common (rates, administration, etc.) (item 17)		15·892	15·690
27	Gross total (items 21, 25 and 26)		85·857	84·765
28	Less cost of other activities additional to deductions in item 24		1·092	
29	Net total as above		84·765	

Deduction for other activities $\frac{1\cdot092 \text{ (item 28)}}{85\cdot857 \text{ (item 27)}} = 1\cdot272\%$ of total costs

Charges on assets $\frac{55\cdot910 \text{ (item 21)}}{679\cdot61 \text{ (item 1)}} = 8\cdot227\%$ of fixed assets

(3.2) Overhead Charges and Operation

The final stages of cost-relating concern the treatment of the three totals in items 21, 25 and 26 of Table 2, namely those which are assets-related, consumer-related and common. As regards

*The actual composition of this income is as follows:

	£ × 10^6
Rentals of meters and apparatus	3·571
Income from public-lighting maintenance	1·547
Surplus on contracting and sales	0·787
Total	5·905

the total in item 21 (detailed in items 7–10), while these items are all assets-proportional the proportion is not the same throughout, and the question is whether a single average figure can be used without doing violence to the estimate. In other words, having divided the asset capital cost between demand and consumers, will a uniform percentage on this cost serve to divide the overhead charges between the two with sufficient accuracy for the present purpose? This question requires separate consideration.

(3.2.1) **Depreciation.**

The actual sums paid in depreciation (item 7) expressed as a percentage of the fixed assets (item 1) amount to 3·31%. By taking separately the assets cost related to consumers in Table 1 and (by difference) those related to demand, and by allocating life estimates to each variety of asset as listed in Appendix 43 of the B.E.A. Second Report, it is possible to calculate the weighted mean lives of the two totals. The results of this calculation are as follows (the percentages are on a straight-line basis, i.e. 100/life):

	Weighted mean life	Corresponding percentage
	years	%
Consumer-related ..	24·0	4·16
Demand-related ..	30·9	3·24
Difference		0·92
Overall	27·7	3·61

All these figures require to be scaled down so as to correspond to the actual overall rate paid of (3·31%), which means that the difference between the correct rates for the consumer and demand groups is approximately 0·85%.

(3.2.2) **Interest.**

Since the interest payments made by the Authority are related to the various loans and cannot in any way be associated with particular groups of assets, it follows that there is no reason for using different rates of interest for different assets, and a single overall figure is the only possible basis of allocation.

(3.2.3) **Rents, Insurance, etc.**

This is only a small item in the total, and it is neither necessary nor practicable to attach it in different proportions to the consumer-related and the demand-related assets.

(3.2.4) **Distribution Working Costs.**

The costs of operation, repairs and maintenance cannot be regarded as related to assets in quite so rigid a manner, since some classes of assets involve a bigger proportion of operating costs than others. The alternative would be to relate them in some way to maximum demand and/or consumers, but since the assets themselves are divided only into two groups, demand-related and consumer-related, there seems no valid reason to attach operating costs any more strongly to the one group than to the other, nor is there any quantitative basis on which such a differentiation could be based. The decision was therefore to treat operation and maintenance in exactly the same way as interest charges.

(3.2.5) **Final Result.**

The above items altogether amount to 8·227% of the assets cost (Table 2, item 21 and footnote). The foregoing examination shows that, strictly speaking, two separate percentages differing by about 0·85% and having a weighted mean of 8·227% should be used for the two groups of assets. This would provide a higher depreciation rate for the consumer-related assets, corresponding to their shorter mean life, and a lower rate for the demand-related assets. As in many other decisions, it is necessary to choose between the rival merits of accuracy and simplicity, and in this case a uniform percentage has been used throughout. This will have the effect, mentioned in the footnote to Section 2.3, of weighting the scales very slightly in the direction away from consumer costs, but the effect would probably not be discernible in the fourth significant figure of the tabulated results.

(3.3) Consumer-Related Expenses

Just as in the case of the capital assets, certain of the expenses in the revenue account can be related directly to the number of consumers. This relating has been rendered very much easier and more precise by a rearrangement of accounts made in the Fifth Annual Report (1952–53 and retrospectively for the 1951–52 figures). The new arrangement shows two groups of costs which can be regarded as wholly consumer-related, namely meter reading, billing and collection, and consumer service. From the latter is deducted the amount attributable to non-electrical activities, and the net total is given in item 25.

(3.4) Common Costs

It is usual to regard expenses such as administration as a common cost or burden not related to output in any way and therefore incapable of precise allocation. On critical examination, however, it will be found that there are hardly any non-output-related costs in electricity supply, provided that the term "output" is interpreted sufficiently widely. In most productive enterprises there are what are called "economies of scale," i.e. if one enterprise is twice as large as another (giving twice the output), its costs will usually be less than twice as great. But in modern electricity supply there are virtually no economies of scale. It is true that a large turbo-alternator or transformer is more efficient than a small one and may cost less per kilowatt, but usually an expansion of power-station capacity is effected by installing more units of a standard size rather than larger units. Similarly with transmission and distribution, a reinforcement or additional line usually involves more units in parallel rather than bigger units. Moreover, with lines and cables, larger size does not (as with machines) mean a larger efficiency. As an overall result, the cost per kilowatt of a big supply system is not necessarily any lower than that of a medium-size system.

What are commonly thought to be economies of scale are, in fact, merely economies of concentration, due, for example, to supplying more electricity to the same consumers or within the same area, whereas, if there is a corresponding increase in the number of consumers and area served, no such economy occurs. Broadly speaking, therefore, if an undertaking grows to twice its size in every respect, supplying twice as many kilowatt-hours and kilovar-hours, having twice as large a maximum demand and serving twice as many consumers spread over double the area, its costs will be twice as great.

Rates are a case in point. Frequently treated as unrelated overheads, they are, in fact, levied on property according to the value of the business carried on therein, which in this case is the supply and sale of energy, power and similar services. In view of the patent fact that in electricity supply the payment in lieu of rates is actually adjusted according to the energy sold, it would be absurd to regard rates as not being output-related.

Even the element of management, which is generally regarded as a typical common cost since it cannot be related specifically to kilowatt-hours, kilowatts, etc., is roughly proportional to the size of the undertaking as a whole. It is noteworthy in this connection that when two adjacent undertakings are merged into one (or 550 into 15) there is very seldom any material reduction in the total personnel.

This suggests that almost all the so-called unrelated or common costs and general overheads (excluding items like capital charges

on plant associated with particular functions) are, in fact, directly proportional to the whole body of output or service rendered. Since this output has been identified and measured under the three major service variables to which specific costs have already been related, it is only logical to attach the remaining (size-related) costs under the same three heads and to add them *pro rata* to the amounts which are already there. With some items a greater precision could have been obtained, but again at the cost of simplicity. Thus, the payment in lieu of rates could have been distributed according to the formula used in sharing it amongst the Electricity Boards. An assay on these lines was made, but the effect was insufficient to change even the fourth significant figure of the results.

The treatment is shown in Table 3, items 20–22. The amount

Table 3

National Totals

Data and Assumptions

Item		Source*	
			$\times 10^3$
1	Consumers, total	[Appendix 5]	13 504
2	Consumers, London	[Appendix 5]	1 641
3	Consumers, excluding London	(1) − (2)	11 863
			£ $\times 10^6$
4	Consumer-related assets, London	(2) × 18/1 000	29·54
5	Consumer-related assets, excluding London ..	(3) × 15/1 000	177·94
6	Consumer-related assets, total	(4) + (5)	207·48
7	Fixed assets, total	[A. 16]	679·61
8	Demand-related assets	(7) − (6)	472·13
			MW
9	Bulk-supply maximum demand	[Derived Appendix 5]	12 816
			kWh $\times 10^6$
10	Bulk-supply net energy purchased	[Appendix 5]	54 826
11	Energy sold to consumers	[Appendix 5]	49 708
12	Energy lost in transmission and distribution ..	(10) − (11)	5 118
13	Loss ratio	(12)/(11) × 100	10·29%
			£ $\times 10^6$
14	Bulk-supply cost	[C. 1]	170·21
15	Bulk-supply demand cost	4·125 × (9)	52·86
16	Bulk-supply energy cost	(14) − (15)	117·35

Schedule of Costs

Item		Energy-related		Demand-related		Consumer-related		Total
		Source	Cost £ $\times 10^6$	Source	Cost £ $\times 10^6$	Source	Cost £ $\times 10^6$	£ $\times 10^6$
17	Bulk-supply cost	(16)	117·35	(15)	52·86			170·21
18	Assets-proportional cost			8.227% of (8)	38·84	8·227% of (6)	17·07	55·91
19	Directly consumer-related					Table 2 (25)	13·17	13·17
20	Sub-total directly related		117·35		91·71		30·23	239·29
21	Proportions (approximately)	49%		38%		13%		
22	Common costs, Table 2 (item 26) ..	0·49 × 15·69	= 7·69	0·38 × 15·69	= 5·96	0·13 × 15·69	= 2·04	15·69
23	Sub-total distribution	(22)	7·69	(18) + (22)	44·80	(20) + (22)	32·27	84·76
			d./kWh		d./kWh		d./kWh	d./kWh
24	Bulk-supply cost per kWh purchased ..	$\frac{(17)}{(10)} \times 240$	0·514		0·231			0·745
25	Distribution loss on bulk-supply cost ..	(13) × (24)	0·053		0·024			
26	Distribution expenditure per kWh sold	$\frac{(23)}{(11)} \times 240$	0·037		0·216		0·156	
27	Total distribution cost	(25) + (26)	0·090		0·240		0·156	0·486
28	Grand total	(24) + (27)	0·604		0·471		0·156	1·231
29	Total on functional basis	0·604d. per kWh sold to consumers		$\frac{(17)+(23)}{(9)}$ = £7 12s. 5d. per annum per kW of bulk supply		$\frac{(23)}{(1)}$ = £2 7s. 9½d. per annum per consumer		

* References in square brackets are to the B.E.A. Fourth Annual Report. Figures in round brackets refer to items in this Table or in other Tables when specified.

† No data are available for the two components of the cost of bulk supplies purchased from outside sources. The present assumption is that all the kilowatts are purchased at £4 2s. 6d., the remainder of the cost being for kilowatt-hours. Inter-Area-Board bulk transactions are excluded.

of common costs requiring to be distributed, consisting of payment in lieu of rates and all administration and general charges which cannot be directly related, totals £15·690 × 10^6 (Table 2, item 26). The total costs of supply (including bulk-supply costs) which can be directly related are in the approximate proportions 49% for energy, 38% for demand and 13% for consumers. The indirect allocations are then 49, 38 and 13% of £15·69 × 10^6 respectively.

(3.5) Effect of Distribution Losses

The cost of all losses occurring beyond the bulk-supply point must be regarded as a distribution cost, but it appears only when costs are expressed per kilowatt-hour. There is no loss expenditure as such in pounds, and the cost arises only because certain of the generation coal cost is dissipated in distribution, and the corresponding energy does not reach the consumer. There is a loss both in kilowatts and in kilowatt-hours, and hence there is an element of distribution cost due to losses in both the demand-related and the energy-related components. Since figures are not available for the demand loss, the calculation has to be made using the energy loss-ratio in both cases.

As an example of the calculation, the mean bulk-supply running charge is 0·514d. per kWh purchased (Table 3, item 24). If there were no distribution losses, the cost per kilowatt-hour sold would be just the same, but owing to losses the denominator is reduced and the quotient becomes 0·567d. per kWh sold to consumers. The difference, namely 0·053d. per kWh sold, is therefore attributable to distribution losses. The difference can be calculated more accurately by multiplying the bulk-supply cost by the loss ratio (energy lost)/(energy sold). The same ratio is employed in finding the distribution loss on the kilowatt cost.

The total costs are shown on two different bases in the last two lines of Table 3. It will be noted that the estimated mean consumer cost throughout the country is 47s. 9½d. per annum. When adjusted for the assumed difference in consumer-related assets, this becomes 52s. 1½d. for London and 47s. 2½d. elsewhere (see Section 4.1.3).

(3.6) Differentiation between Consumer Types

So far, consumer costs have been taken as a single overall average as though the *per capita* costs were the same for all types of consumer. This is clearly not the case. With the consumers grouped into three main classes, namely domestic (plus farm), commercial, and industrial (plus public lighting and traction), there are the following *prima facie* reasons for expecting the second and third classes to have bigger consumer costs than the first:

(*a*) Commercial consumers have on the average nearly four times as great, and industrial consumers nearly 120 times as great, a consumption per head as domestic consumers. Even excluding the very large consumers on special agreements, whose consumer costs are not appropriate for averaging, there are likely to be more administration and other costs per consumer in the latter groups.

(*b*) There are approximately nine times as many domestic consumers as commercial, and over 70 times as many domestic consumers as industrial. It must be expected that there will be proportionally heavier expenses in dealing with a small group than a large one.

(*c*) Commercial and industrial consumers will, on the average, occupy larger premises which are likely to involve longer service connections. Furthermore, 3-phase services of a given capacity will cost more per yard than single-phase services.

(*d*) Industrial consumers will usually require more expensive meters, and more frequent metering and billing, and there may be complications such as power factor which will affect the consumer costs.

On the other hand, there is a certain difference in the opposite direction, inasmuch as many industrial and some commercial consumers are supplied at high voltage and make no use of the low-voltage mains. Since a small proportion of the cost of underground mains is consumer-related, the domestic-consumer cost should on this score be slightly higher.

The most obvious way of dealing with these variations would be by some system of weighting. A possible scheme is shown below, based on a ratio of 1 : 1·5 : 3 for domestic, commercial and industrial consumers respectively. (The London figures are taken as 10% higher in each case.) This weighting gives the same total costs as the single overall figure with the existing numbers and types of consumer.

Possible Consumer-Cost Weighting

		Excluding London	London only
Overall average	.. .. ..	.. 47s. 2½d.	52s. 1½d.
Weighted equivalent	Domestic and farm	.. 44s. 0d.	48s. 5d.
	Commercial ..	.. 66s. 0d.	72s. 7d.
	Industrial, etc.	..132s. 0d.	145s. 2d.

Obviously there is an infinite number of possible weightings which will give the same total, and the above is inserted merely for illustration purposes.

The effect which such weighting would have on the cost allocation would depend on what variations there are throughout the 14 areas in the proportions of the different consumer groups. The proportion of the industrial consumers shows the biggest variation, namely from 0·3 to 2·5% of the total. (Somewhat surprisingly, the biggest proportion of industrial consumers is not found in the areas with the biggest proportion of industrial consumption. In fact, London, with a percentage industrial consumption less than half that of some of the more highly industrialized areas, has a ratio of industrial to total consumers nearly twice as great as that of any other Board.) The proportion of commercial consumers shows much less variation, namely from 8·3 to 12·0%.

A weighting adjustment has not been employed in the present analysis for two reasons. First, the data for an accurate weighting are absent and any scheme such as that illustrated above would be largely empirical, although it might be possible to assign values for some of the specific cost differences. Secondly, the effect would only just appear in the fourth significant figure of the calculation. It will be realized that it is only the difference in proportions in the different areas which can affect the figures, since the overall cost total is already determined.

Even if a heavy weighting is given to the industrial consumer-cost, it does not affect the figure greatly because there are proportionally so few of them. The commercial consumers are much more numerous, but their cost weighting would also have little effect on the cost allocation for two reasons. First, the weighting could not be very heavy, since the commercial consumer-cost would not so greatly exceed the domestic; and secondly, the differences in the proportions of commercial consumers between the different Boards are not very great.

(4) APPLICATION TO INDIVIDUAL BOARDS

(4.1) Procedure

The foregoing method as used on the national totals is now applied to each Board in turn, using broadly the same procedure and in certain respects the same constants. The procedure is described below and is carried out in the lower part of Table 4, using the constants derived in the upper part. As before, all costs are expressed in pence per kilowatt-hour sold to the Board's consumers. The source references in square brackets are to the Fourth Annual Report. The figures in round brackets refer to items in this Table or other Tables where specified.

Table 4

CALCULATIONS FOR TWO AREA BOARDS

Item	Element	London	South-Eastern	Source
1	Total bulk-supply cost, £ × 10^6	18·90	10·68	[C.1, line 6]
2	Sales to other Area Boards, £ × 10^6	0·11	0·34	[V(*a*) in Area Board Reports]
3	Net cost, excluding inter-sales, £ × 10^6	18·79	10·34	(1) − (2)
4	Simultaneous maximum demand of net purchases, MW	1 433	714	[Derived, Appendix 5]
5	Bulk-supply net purchases for sale to own consumers, kWh × 10^6	5 300	3 020	[Appendix 5]
6	Total sales to consumers, kWh × 10^6	4 670	2 660	[Appendix 5]
7	Losses in transmission and distribution, kWh × 10^6	630	360	(5) − (6)
8	Loss ratio, %	13·5	13·7	(7)/(6) × 100
9	Bulk-supply power cost at £4·125, £ × 10^6	5·91	2·95	(4) × 4·125/1 000
10	Bulk-supply energy cost, £ × 10^6	12·88	7·39	(3) − (9)
11	Number of consumers, ×10^3	1 641	984	[Appendix 5]
12	Area served, square miles		3 095	[Appendix 5 of Third Report]
13	Fourth root of area per megawatt		1·44	$\sqrt[4]{(12)/(4)}$
14	Annual charges on demand-related assets, £/kW	3·56	2·80	1·94 × (13) (3·56 for London)
15	Demand-related common cost, £/kW	0·46	0·46	
16	Total annual costs, £/kW	4·02	3·26	(14) + (15)
	Energy-related costs per kilowatt-hour sold to consumers			
17	Bulk supply, d.	0·583	0·587	$\frac{(10) \times 240}{(5)}$
18	Distribution loss on bulk supply, d.	0·079	0·081	$\frac{(8) \times (17)}{100}$
19	Common cost, d.	0·037	0·037	Table 3, item 26
20	Total, d.	0·699	0·705	
	Demand-related costs per kilowatt-hour sold to consumers			
21	Bulk supply, d.	0·268	0·234	$\frac{(9) \times 240}{(5)}$
22	Distribution loss on bulk supply, d.	0·036	0·032	$\frac{(8) \times (21)}{100}$
23	Distribution charges and common cost, d.	0·296	0·211	$\frac{(16) \times (4) \times 240}{(6)}$
24	Total, d.	0·600	0·477	
	Consumer-related costs per kilowatt-hour sold to consumers			
25	Total	0·220	0·209	(11)/(6) × 566½ for S.E. (11)/(6) × 625½ for London

(4.1.1) **Energy-Related Element.**

The running cost of the bulk supply is taken as equal to the total net bulk-supply cost less 4·125 times the simultaneous maximum demand of the net bulk supply. The division of this by the net energy purchased (i.e. for sale to the Board's own consumers) gives the total running cost per kilowatt-hour purchased, and also per kilowatt-hour sold if there are no distribution losses (item 17). The energy-related element in the cost of distribution losses (item 18) is the bulk-supply running cost multiplied by the loss ratio for the particular Board. The energy-related share of the common cost of distribution (item 19) is taken as being the same for every Board and for the whole country, namely 0·037d. per kilowatt-hour sold to consumers (as in Table 3, item 26).

(4.1.2) **Demand-Related Element.**

The standing cost of the bulk supply (item 21) equals 4·125 multiplied by the Board's ratio of kilowatts of maximum demand to kilowatt-hours of bulk-supply purchase. The demand-related element in the distribution loss (item 22) is this standing cost multiplied by the Board's loss ratio.

The demand-related assets per kilowatt of maximum demand are obtained from the formula in Section 2.5, including the adjustment for load density except in the case of London, and the annual charges per kilowatt are 8·227% per annum of these assets as shown at the foot of Table 2. (Item 14: 23·60 × 8·227% = 1·94, which is then multiplied by the fourth root of the area per megawatt. For London, the constant 43·24 × 8·227% = 3·56.) The demand-related common costs are taken to be the same per kilowatt of maximum demand in each Board and throughout the country. [Item 15: the total of £5·96 × 10^6 (Table 3, item 22) divided by the aggregate maximum demand, 12·81 × 10^6kW, equal £0·46d./kW.] The sum of these two annual charges (item 16) is then converted to pence per kilowatt-hour by multiplying by the Board's ratio of kilowatts of maximum demand to kilowatt-hours sold to consumers (item 23).

(4.1.3) **Consumer-Related Element.**

The consumer-related assets are taken as £18 per consumer for London and £15 elsewhere. Annual charges are 8·227% of this, to which must be added the directly consumer-related costs and the allocation of common costs as follows.

	Excluding London	*London only*
	£ p.a./consumer	£ p.a./consumer
Distribution charges at 8·227%	on £15: 1·234	on £18: 1·481
Directly consumer-related, Table 3, (item 19)/(item 1)	0·975	0·975
Common costs, Table 3 (item 22)/(item 1)	0·151	0·151
Total	£2·360	£2·607
Total in shillings and pence ..	47s. 2½d.	52s. 1½d.

The resulting constant is then multiplied by the Board's ratio of number of consumers to number of kilowatt-hours sold (item 25). (N.B. In some of the figures used in the above text the factor of 240 required to convert to pence is omitted for simplicity.)

(4.2) Results

The individual Boards' results are displayed in Table 5, all figures being multiplied by 100. For comparison, the national figures are shown in the last line, taken from items 27 and 28 in Table 3. As a check on the figures, the first three items were added in each case and multiplied by the total energy sold by the Board. The sum of these products minus the total Boards' consolidated loss for the year equals the total revenue obtained from the sale of electricity. In other words, the fourth item is merely the sum unaccounted for in the particular Board's case, and when these sums are weighted by the energy sold the total (taking signs into account) is zero.

In the last column the amounts unaccounted for have been expressed as percentages of the distribution cost, since—the bulk-supply costs being precisely calculable—it is only in the distribution cost calculation that any discrepancy should arise. This, however, has the effect of exaggerating the magnitude of the discrepancy. It will be seen that the largest single discrepancy is 21% of the distribution cost (9% of the total cost) and the figure is less than 5% in nearly half the cases. In other words, while there are very big differences in cost and therefore in selling price, ranging from 0·97d./kWh in South Wales to 1·6d./kWh in London—a range of 65%—the difference has been scientifically accounted for in terms of specific cost elements except for discrepancies of a very few per cent.

Even these small discrepancies show a certain uniformity, since all the excesses are in the south of England and the shortfalls are in the Midlands and north. Besides the cost variations accounted for in this calculation there would therefore appear to be a slight geographical "drift" which tends to make costs higher in the south than in the north. This geographical tendency is well shown in Fig. 3, in which the discrepancies are plotted in the order in which the Boards are scheduled in the 1947 Act, which is roughly from the south of the country to the north. (The crosses refer to 1951–52.) After allowance for the fact that London has been given an artificial rating, but for which its point would lie far higher (see dotted arrow), the points lie roughly on a falling straight line from the southern to the northern Boards.

A basis has thus been established both for comparing the performances and progress of different Boards and for splitting up the costs of each Board into the energy, demand and consumer components. It will be seen that costs materially in excess of the calculated ones are indicated for the Southern, South Western, South Eastern, Eastern and London Boards (the latter

Table 5

RESULTS FOR ALL AREA BOARDS

Area Board	Total cost and make-up of selling price						Distribution cost only				
	Energy-related	Demand-related	Consumer related	Discrepancy unaccounted for	Net surplus	Selling price	Energy-related	Demand-related	Consumer related	Total related	Discrepancy
	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	d./kWh $\times 10^{-2}$	%
London	69·9	60·0	22·0	5·0	2·5	159·4	11·6	33·2	22·0	66·8	7·5
South Eastern	70·5	47·7	20·9	6·9	−0·9	145·1	11·8	24·3	20·9	57·0	12·1
Southern	68·8	49·8	18·9	7·5	−0·5	145·5	10·2	26·2	18·9	55·3	13·6
South Western	65·3	55·6	22·8	7·4	−2·3	148·8	10·8	31·2	22·8	64·8	11·4
Eastern	68·8	48·0	17·9	3·8	0·7	139·2	10·7	25·1	17·9	53·7	7·1
East Midlands	54·5	49·2	15·6	−0·7	−5·2	113·4	9·4	25·7	15·6	50·7	−1·3
Midlands	58·5	44·9	11·8	−1·9	−2·4	110·9	7·7	21·4	11·8	40·9	−4·6
South Wales	48·2	37·2	9·3	−0·7	2·6	96·6	6·8	18·9	9·3	35·0	−2·0
Mersey and North Wales	60·6	41·8	13·0	−0·4	0·8	115·8	8·7	21·3	13·0	43·0	−0·9
Yorkshire	52·7	42·9	13·5	−4·8	−0·9	103·4	7·3	20·0	13·5	40·8	−11·8
North Eastern	53·4	41·9	13·6	−1·2	−1·2	106·5	8·5	22·0	13·6	44·1	−2·7
North Western	58·3	44·8	13·4	−1·9	0·9	115·5	8·3	21·2	13·4	42·9	−4·5
South East Scotland ..	59·5	54·7	18·5	−9·1	−2·6	121·0	9·2	29·5	18·5	57·2	−16
South West Scotland ..	60·3	50·6	15·3	−10·4	−4·3	111·5	7·7	25·5	15·3	48·5	−21
Whole country	60·4	47·1	15·6		−0·6	122·5	9·0	24·0	15·6	48·6	
Item No.	1	2	3	4	5	6	7	8	9	10	11
Source	Table 4, (20)	Table 4, (24)	Table 4, (25)	Subtraction	[C.1, 24]×240 / Table 4 (6)	[A.5]	Table 4, (18) + (19)	Table 4, (22) + (23)	Table 4, (25)		Table 5, (4)/(10)

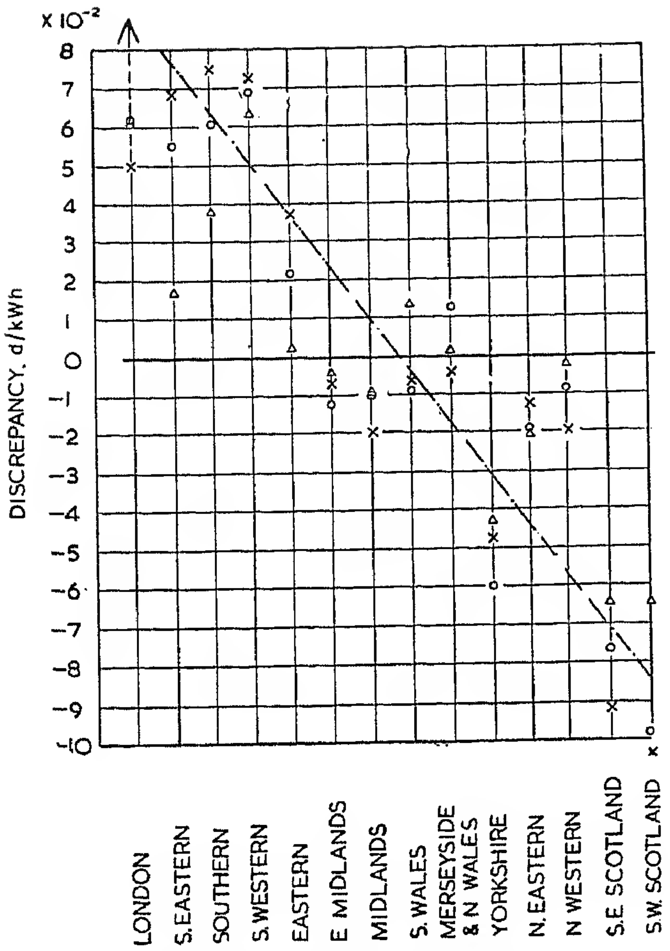

Fig. 3.—Area Board discrepancies.

Positive discrepancies indicate that the actual cost exceeds the notional cost, and negative discrepancies that it is less than the notional cost.

× × × 1951–52.
○ ○ ○ 1952–53.
△ △ △ 1953–54.

even after allowing for the "London weighting"). On the other hand, the two Scottish Boards and the Yorkshire Board have costs substantially below the calculated averages. The remaining Boards are all slightly under the calculated figures.

(5) RESULTS FOR 1952–53 AND 1953–54

(5.1) Method

In the comparison of 1952–53 with the previous year, it will be seen that the aggregate maximum demand and the total fixed assets both increased by approximately 8% and the number of consumers by nearly 3%. It follows that, however the assets are apportioned between demand and consumers, the quotient of assets per megawatt or per consumer can show only very minute changes. For convenience in recalculation, the assets per consumer have been taken as exactly the same as in the previous year, namely, £18 in London and £15 elsewhere. Such small changes as have actually occurred in the quotients are thereby all assigned to the assets per megawatt. A new formula was therefore developed corresponding to that in Section 2.5 to fit the 1952–53 asset figures. A complete recalculation was then carried out on the lines of Tables 2–4, applying precisely the same methods to the 1952–53 figures, first for the whole country and then for the individual Boards.

Since these calculations were completed, a further set of data has been made available, namely the Electricity Boards' Annual Reports for 1953–54. This situation presented the author with a difficult choice. By using exactly the same procedure for this new year as that described for 1952–53 one could maintain an unbroken continuity in the three years, and if no future figures were ever to be used this would probably be the best (as it is the easiest) course to pursue. On the other hand, there are obvious dangers in applying a framework designed for 1951 to the figures for 1953. If the process is to be continued in still later years, the framework will very soon show cracks or will have to be entirely recast. The final decision was to make a small break in the present year by assuming more up-to-date figures for the mean cost of consumer-related assets.

Taking the major element, namely cost of services, the average cost of the services installed in the six post-vesting years has been £17 13s. 0d. per additional consumer. There are no published figures for pre-vesting cost, but, presuming this to have been in the neighbourhood of £4–£5 per service, it is obvious that, as the proportion of post-vesting expenditure increases, the mean cost per service must increase, and hence the consumer-related assets as a whole.

The same *a priori* reasoning could be applied to the demand-related assets, and since the total assets are known it might appear a simple matter to assume the same rate of increase in both and of such a magnitude as to give the correct total. This is not possible, because of the erratic nature of the denominator in the case of the assets per kilowatt. With the other two quotients, namely those relating to consumers and energy, this difficulty does not arise. The number of consumers shows a fairly steady annual increase, and although the energy may fluctuate more widely, there are corresponding fluctuations in cost (on account of coal), so that the cost quotients vary fairly smoothly from year to year. But with the demand-related cost the denominator is the maximum demand on the bulk-supply system, which may fluctuate widely without any immediate correspondence in either the assets or the annual costs to the industry. In 1953–54 the demand increased by 12½%, largely because of an exceptionally cold spell in February, 1954, while the total assets increased by only 8½% and the energy by 6½%. Any reasonable allocation of assets per actual kilowatt for this year would therefore show a decrease rather than an increase. Speaking generally, while costs per kilowatt-hour and per consumer are likely to show smooth annual trends, the costs and assets per kilowatt will fluctuate with each year's weather, and only the long-term trend is significant.

For the present calculation the assumption was made that, if the figures for 1953–54 could be adjusted to 1951–52 weather conditions, the demand would have increased in the same ratio as the energy increased; in other words, with a long-term weather adjustment the load factor would have been the same in the two years. A calculation then showed that a 7% increase in the two years in both assets per consumer and assets per equivalent kilowatt would just account for the actual total assets increase. Possibly the assets per kilowatt should increase at a fractionally higher rate, because of the greater rate of investment and therefore greater rate of increase in the post-vesting proportion. The final decision was therefore to assume a 6¾% increase in the assets per consumer, giving a figure of £16 per consumer outside London and £19 4s. 0d. per consumer in London.

(5.2) National Results

Table 6 shows the results of the calculations for the country as a whole for the two years, and the percentage increase in each year. The upper portion shows the average make-up of the selling price corresponding to Table 3, item 28, and the last line of Table 5. The lower portion shows the costs on a functional basis corresponding to Table 3, item 29.

It will be seen that the country's overall cost per kilowatt hour increased by 6·4% in 1952–53 and by 3·7% in 1953–54. The second figure was lower largely because the energy increased by nearly twice as great a percentage in the second year as in the first without an (immediate) corresponding increase in many of the costs. The increase in the components which make up the overall cost are shown in the first three lines of the Table, and if

Table 6

National Cost Components for 1952–53 and 1953–54

Component	1952–53	Increase over previous year	1953–54	Increase over previous year	Increase of 1953–54 over 1951–52
On energy-sold basis.	d./kWh	%	d./kWh	%	%
Energy-related	0·638	5·7	0·678	6·2	12·4
Demand-related	0·512	8·6	0·514	0·4	9·0
Consumer-related	0·159	2·1	0·166	4·3	6·5
Total cost	1·309	6·4	1·358	3·7	10·3
Net surplus	0·007		0·023		
Selling price	1·316	7·5	1·381	4·9	12·8
On a functional basis.					
Energy-related	0·638d./kWh	5·7	0·678d./kWh	6·2	12·4
Demand-related (per kilowatt of bulk supply)	£7 18s. 8½d. p.a.	4·1	£7 12s. 6d. p.a.	−4·0*	
Consumer-related (per consumer)	£2 9s. 2d. p.a.	2·9	£2 10s. 8½d. p.a.	3·1	6·1

* Decrease due to disproportionate increase in the maximum demand. With equivalent weather conditions to those in 1951–52 there would have been an increase of approximately 6%, and a two-year increase of approximately 10½%.

space permitted these separate increases could be compared with the changes that have occurred each year in fuel prices and thermal efficiencies, plant prices and other cost items. The broad picture is that the three groups of costs can be put in the order: energy, demand and consumers, both in their absolute values and in their rates of increase. When expressed on a functional basis the 2-year increases are approximately 12%, 10½ and 6% respectively, the figure for demand-related costs being adjusted to comparable weather conditions.

For reference purposes, Table 7 has been drawn up to show certain changes in the two years. The first four lines are derived directly from the Annual Reports, while the last two refer to the calculations of the present paper. Two of the major elements which make up the distribution demand-related and consumer-related costs are the capital charges and the operation and maintenance costs, and both of these can usefully be expressed as ratios of the assets cost. These ratios changed as shown in the bottom lines of the Table. It will be seen that capital charges maintain a fairly steady ratio with a slight upward trend. The operating cost shows a decreasing ratio to assets costs, but could the assets have been expressed in kilowatt capacity rather than cost, the operating cost ratio would probably have shown an increase. (It follows from the much higher unit cost of new plant that the rate of increase of assets cost will be greater than the rate of increase of capacity.)

Table 7

Other Comparison Data

[The costs (last three lines) are for distribution only.]

	Increase during		
	First year	Second year	Two years
	%	%	%
Energy consumption	3·6	6·5	10·3
Maximum demand on bulk supply	8·0	12·6	21·6
Number of consumers	2·6	3·8	7·6
Total fixed assets cost	7·8	8·4	16·9
Capital charges as ratio of assets cost	3·4	−1·0	2·4
Operating costs as ratio of assets cost	−2·1	−6·0	−8·0

(5.3) Individual Results

Table 8 shows three lists of the Boards arranged in order of

Table 8

Boards in Order of Discrepancy

(The figures are in ten-thousandths of a penny per kilowatt-hour and indicate how far the actual cost exceeds the notional cost, or by how much the excess has increased. Negative values therefore indicate a relatively low or reduced cost. A position above the gap indicates a performance above the average, and vice versa.)

1951–52		1953–54		Two-year changes			
					1951 to 1952	1952 to 1953	Total
S.W. Scotland	−1 040	S.E. Scotland }	−644	S. Eastern	−139	−389	−528
S.E. Scotland	−913	S.W. Scotland }		Southern	−147	−224	−371
Yorkshire	−480	Yorkshire	−431	Eastern	−159	−201	−360
N. Western	−193	N. Eastern	−198	S. Western	−42	−64	−106
Midlands	−187	Midlands	−90	N. Eastern	−67	−11	−78
N. Eastern	−120	E. Midlands	−40				
S. Wales	−69	N. Western	−22	E. Midlands	−52	80	28
E. Midlands	−68			Merseyside and N. Wales	167	−119	48
Merseyside and N. Wales	−38	Merseyside and N. Wales	10	Yorkshire	−114	163	49
		Eastern	18	Midlands	95	2	97
Eastern	378	S. Wales	137	London	119	−7	112
S. Eastern	691	S. Eastern	163	N. Western	109	62	171
S. Western	735	Southern	381	S. Wales	−14	220	206
Southern	752	S. Western	629	S.E. Scotland	149	120	269
London		London		S.W. Scotland	52	344	396

merit as measured by their discrepancies. In the first they are listed in the reverse order of their discrepancies in 1951–52. The second list shows the same thing for two years later. In the third they are listed in the order of their relative improvement or retrogression in 1953–54 over 1951–52 (figures in last column). The total change in the two years is made up of the two yearly changes shown in the two previous columns, which measure the relative movement each year over the previous year. The word "relative" is a reminder that in each year the discrepancy is calculated from the mean for that year, so that for the Boards as a whole there could not be any overall improvement or retrogression. In Fig. 3 the discrepancies in all three years are plotted in the order in which the Boards are scheduled. The chain-dotted line shows the straight line of best fit in 1951–52, omitting the London Board.

The meaning of the figures in these three lists can be illustrated by taking a single example, such as that of the South Eastern Board which heads the third list. In 1951–52 (first list) this Board had an adjusted or "notional" cost exceeding the year's average by 691 ten-thousandths of a penny per kilowatt-hour. In the next year its discrepancy from the year's average was less by 139 and in the year following it was less by 389, a total reduction of 528 which put it at the head of the third list giving the 2-year changes. The discrepancy in 1953–54 was therefore $691 - 528 = 163$, as shown in the second list, although the improvement was not sufficient in this case to change its position in the list.

No figures can usefully be given in the first two lists for London, owing to the arbitrary handicap in respect of assets relationship. The yearly changes, however, are just as significant for London as for the other Boards. For the sake of comparability the same handicapping was used in the later years, although actually London's asset position has improved and would have justified a somewhat less favourable handicap. Whereas in 1951–52 it was necessary to assume 20% greater assets per kilowatt and per consumer in order to bring London into line with the remainder, the same effect could be produced in 1953–54 by an assumption of a 17% increase.

The figures for the 2-year changes show that, in general, the discrepancies are lessening. Boards having high positive discrepancies in the earlier year have, for the most part, improved their performances, while those with high negative discrepancies (costs below average) have tended to show reduced performances. Put in another way, the chain-dotted line in Fig. 3 would have been less steeply inclined had it been drawn for 1953–54 instead of for 1951–52. While the trend for any particular Board has usually been uniform, notable exceptions were the Merseyside and the Yorkshire Boards, which showed opposite changes in the two years.

When looking at these results it must be borne in mind that the index they portray is extremely sensitive. Out of the totals which make up the Boards' selling prices, all but a very small percentage has been accounted for on technical grounds, and it is only these small discrepancies and their even smaller annual changes that are put under the microscope in Tables 6 and 8 and in Fig. 3.

(5.4) Summary of Changes

The individual Boards' cost increases result from two changes: (*a*) the increases* in each of the three component costs; and (*b*) a change (either up or down) in the discrepancy. The increase (*a*) is broadly the same as for the country as a whole and as shown in Table 6, adjusted for the particular Board's technical characteristics such as the ratios of the demand and the number of consumers to the energy sold. The change (*b*) in the various discrepancies is shown in the second and third parts of Table 8. These figures can be explained by saying that, while the national costs as a whole and therefore those of each Board have gone up on the average by the amounts shown in Table 6, the individual Boards' costs (adjusted for technical differences) have departed slightly from this average, and these departures have got worse in some cases and better in others.

* Although in one year one of these changes was a decrease this was a fortuitous occurrence having no long-term significance, and in order to preserve the spirit of the argument the words "increase" and "up" are employed throughout this Section without qualification.

(6) SUMMING-UP

(6.1) Definitions

The following are precise definitions of the three quantities referred to here and elsewhere. All three are expressed in pence per kilowatt-hour sold to consumers.

(*a*) *Actual Cost* as measured by the revenue from retail electricity sales, less the net surplus (or plus the deficit) divided by the energy sold to consumers.

(*b*) *Notional Cost* built up from the three functional components using the technique developed in the paper.

(*c*) *Discrepancy*, namely (*a*) minus (*b*).

(6.2) Interpretation

The discrepancy can be interpreted in either or both of two ways. First, a discrepancy, whether positive or negative, may indicate a shortcoming in the costing technique. This would obviously apply when and to the extent that the discrepancies showed a definite trend (as, in this case, a geographical one). Secondly, a positive discrepancy indicates a bad mark, and a negative discrepancy a good mark, for the Board concerned.

When discrepancies for successive years are available an even more useful interpretation becomes possible, since most of the variables likely to confuse the results will then be eliminated. A change to a smaller positive figure or a larger negative one indicates that the Board in question has improved its economic efficiency relative to the other Boards, i.e. its change from its performance in the previous year has been better than the average change of all the 14 Boards.

There are two questions which a Board's management may ask, namely are we operating at the highest economic efficiency which our particular circumstances permit, and how is this efficiency changing with time? The paper makes no attempt at an absolute answer to the first question, but it does assist in obtaining a relative answer as compared with the other Boards, and, for the second question, as compared with other years. The questions are at all times difficult to answer because of the number of variables involved, e.g. bulk-supply cost of energy and of power, the Board's "output" in energy, power and reactive components, in the number of consumers served and the differences of terrain. The paper is an attempt to compensate for these variables.

A particular application lies in plotting a Board's progress from year to year or in estimating the overall effect of some reorganization. It might take several years for the full results to materialize, during which time the effect might be swamped by extraneous changes. On the other hand, immediate comparisons with other Boards are vitiated by the wide differences in kW/kWh, consumers/kWh, area/kW ratios, etc. By the use of the technique here developed, temporal changes are neutralized, because the comparison is carried out on a basis of the mean values for that year throughout the country, and Board-to-Board variations in technical conditions are compensated for by the economic calculus employed. What is left is a very sensitive index to the specific or essential economic efficiency.

(6.3) Scope of Achievement

It will be well to clarify the results by stating precisely what has and what has not been accomplished. The average costs for the country have been split into functionally-related components, and from this has been calculated what each Area Board's costs would be if similar functional relationships were maintained. The overall results do not in any sense say what electricity ought to cost, and if it were suggested, for example, that distribution throughout the country costs more than it should, the paper would adduce no evidence either way.

The separate results, however, enable the Boards to be compared together. On the basis of the country's average costs, the paper estimates what each Board's operation should cost and expresses this in pence per kilowatt-hour sold, allowing for all the known Area differences which could legitimately affect the cost. When this notional cost is compared with the Board's actual cost, a discrepancy either way indicates that some element in the service is costing more or less than it statistically should, either because of a variation in the economic efficiency or because of some inevitable difference in the character of the supply for which the formulae have not provided. In any case a substantial (positive) discrepancy provides at least a *prima facie* case for an examination to establish the cause. Thus, wherever costs exceed this allocated average the difference might be traced to its source, e.g. disproportionately high capital costs. (As an example of this, some correlation can be traced between the departures of individual Boards from the straight lines in Figs. 2 and 3.) Another possible correlation (not studied here) would be with power factor.

One might perhaps set one's sights a little higher and suggest that the figures for the "best" Area on this showing might well serve as a target at which the remainder should aim or show cause for not reaching.

(6.4) Conclusions

The conclusions to be drawn can be summarized as follows:

It is possible to account for the differences in selling prices of the different Boards on a functional basis, except for a small discrepancy rarely exceeding 5–10%.

The discrepancies of the 14 Boards show a marked geographical distribution, costs being higher than the average in the south and lower in the north of the country. This has long been known, but in the past has been difficult to measure.

Individual departures from the average and from the trend can serve as the starting point for an attempt to analyse, and if possible to improve, the economic efficiency.

Annual changes in the discrepancy figures form a sensitive index to changes in relative economic efficiency.

In addition to these conclusions regarding cost totals, there are some useful conclusions regarding cost components, particularly those for the country as a whole. While the principles of cost relating employed here involve nothing new, the methods used and the numerical results, such as those displayed in Table 6, are not without interest.

DISCUSSION ON THE ABOVE PAPER

Before THE INSTITUTION *3rd February, the* SOUTHERN CENTRE, *at* BRIGHTON, *9th February, the* MERSEY AND NORTH WALES CENTRE, *at* LIVERPOOL, *7th March, and the* SOUTHERN CENTRE, *at* SOUTHAMPTON, *23rd March*, 1955.

Mr. C. T. Melling: The limitation of an analysis of Area Boards' costs has been clearly stated by the author: namely that, omitting the special case of London, there are only 13 sets of data. Having regard to this serious initial limitation the author's "best fit" analysis has yielded interesting results.

The other main limitation is that cost, although very important, is only one of several criteria by which Area Boards can be judged, others being:

(*a*) Satisfactory supply to present consumers and extension of networks to supply new consumers.
(*b*) Consumer service: advice on getting best value from electricity; facilities for obtaining modern appliances and wiring installations; repair service.
(*c*) Load development and improvement of load-factor of system.
(*d*) Good public relations.
(*e*) Good employee relations, including satisfactory arrangements for wage and salary negotiations, joint consultation, welfare, safety, education and training.
(*f*) Board's organization in providing the above services.
(*g*) Board's costs in providing the above services.
(*h*) Board's tariffs and other charges to consumers.
(*j*) Board's trading position as a commercial concern.

Most of these criteria are qualitative, and consequently no yardstick can measure a Board's overall merit. The paper is a valuable contribution to cost analysis; the assessment of merit, however, would require a physical examination of each Area.

In making a numerical analysis of capital costs the author has approached the problem from the very logical standpoint of relating costs to kilowatt-hours, demand and consumers, but in the absence of other data he has been compelled to make arbitrary assumptions, some of which are open to qualification.

The correction applied to demand-related capital costs in proportion to the fourth root of the Area serves only as a very round approximation. Some of the Areas contain wide tracts of uninhabited land, mountain or moorland, where cottages and other premises requiring electricity are along valleys or in similar local groupings, whereas other Areas, although not homogeneous, contain no large tracts of country without premises requiring electricity.

I agree with the author in Section 2.6 that the extra complication of correcting for differences in the ratio of kilowatt-hours sold to consumers on high and low voltage would not be justified in his analysis, since any such correction would be extremely difficult—or, indeed, impossible—because many low-voltage consumers, particularly in rural areas, take supply direct from the low-voltage side of a transformer.

A serious limitation to analysis of costs at the present time is the effect of artificial conditions imposed by the scarcity of generating plant and distribution capacity and the effect of these on demand-related costs. Moreover, the basic year of the author's analysis is not necessarily the best year to take, since the maximum demands tended to be lower than in neighbouring years owing to a mild winter. The effect of temperature and climatic conditions tends to be more marked in Areas with a preponderance of domestic demands rather than industrial ones, and this fact tends to vitiate the comparisons the author has shown in Fig. 3 and Table 8, because there a normal rate of growth is assumed. The comparison with other years, therefore, is dependent on the validity of the analysis in the first year, and further consideration is necessary to this climatic effect in its relation to the comparison of one year's results with another's.

One of the main differences between Areas—and, in this respect, there tends to be a geographical distribution—is that in some, particularly in the South—industrial sales are a much smaller proportion of total sales than in others. As the percentage of industrial consumers to total consumers offers no suitable basis for correction, no adjustment has been made for this. It is, however, this difference in consumer types, or rather

difference in types of supply, which forms a useful basis of comparison which has been used with some success.

Domestic and commercial consumers involve a higher cost per kilowatt-hour sold than sales to industrial consumers, and one of the main differences between Areas is the ratio of domestic and commercial energy sold. This factor has been used by the Eastern Electricity Board as one to be regarded when analysing cost data, and Fig. A shows the distribution expenses per kilowatt-hour (corresponding to Item 10 of Table 2 in the paper) plotted against this factor. It discloses the geographical difference in costs, all the five Boards in the South of England having high percentages of domestic and commercial to total sales.

Fig. B shows administration, consumer service, meter reading, billing and collecting costs, and individual aspects of these totals have been examined by the same method.

The same relationships of District costs in the Area are shown in Figs. C and D. There are many physical reasons to account for the wide deviation of points in these curves: number of consumers per square mile; urban or rural districts; number of consumers supplied in the District; number of service centres; details of engineering work as affecting distribution cost, etc.

These curves are intended merely to illustrate another method of approach to the problem of analysis. No single method of approach is adequate—even a combination of methods cannot result in an accurate assessment of merit—but, although one cannot apply a simple yardstick, these comparative analyses provide a rough guide as to which Districts appear capable of improvement in the economic sense. Frequently, a detailed physical examination provides justification for higher costs or, similarly, may provide justification for further improvements where the costs are already low. I think it is in the pin-pointing of matters to be examined that the true value of such broad cost-analysis lies.

Of course, in making analyses of District figures it is not possible

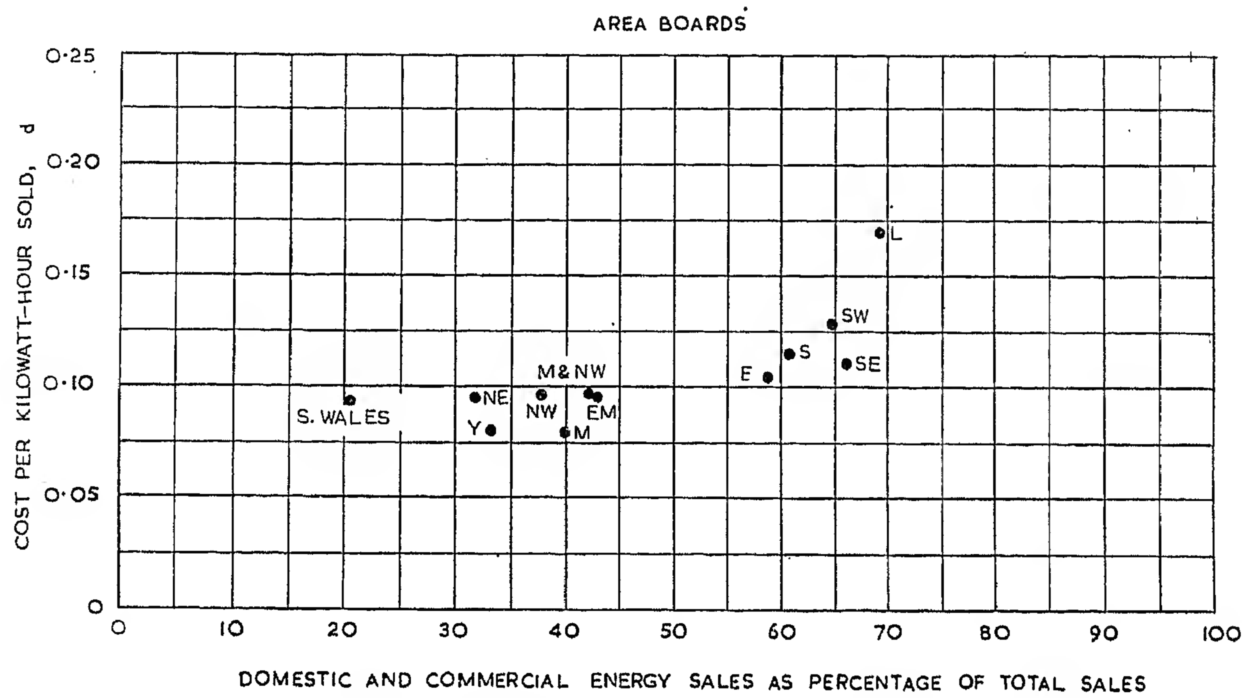

Fig. A.—Distribution expenses (pence per kilowatt-hour) related to domestic and commercial energy sales, as percentage of total sales. Year: 1953–54.

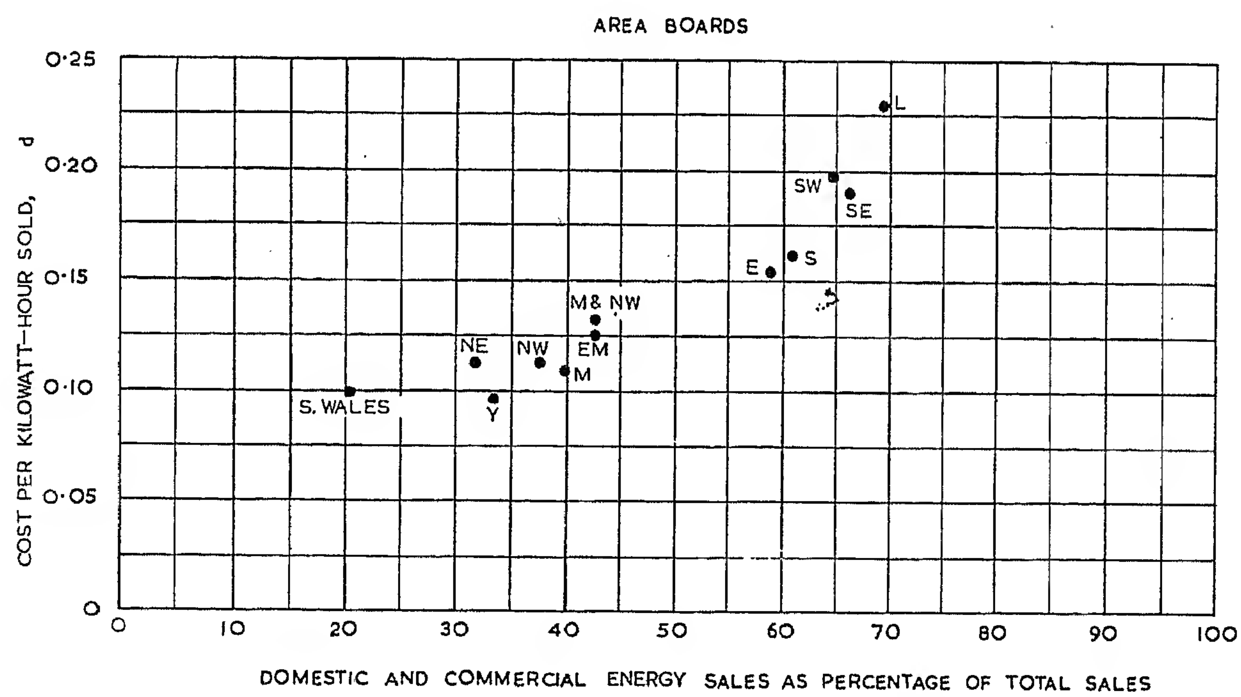

Fig. B.—Administration, consumer service and collection, etc., costs (pence per kilowatt-hour) related to domestic and commercial energy sales, as a percentage of total sales. Year: 1953–54.

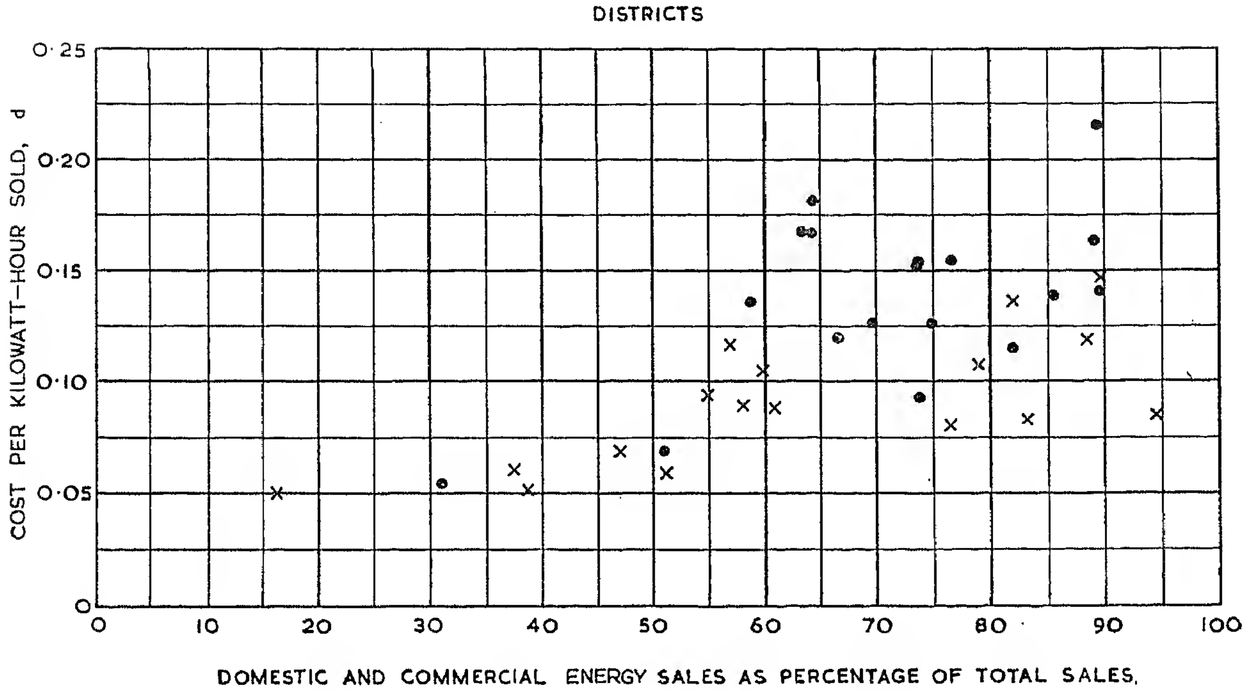

Fig. C.—Distribution expenses (pence per kilowatt-hour) related to domestic and commercial energy sales, as a percentage of total sales. Year: 1953–54.

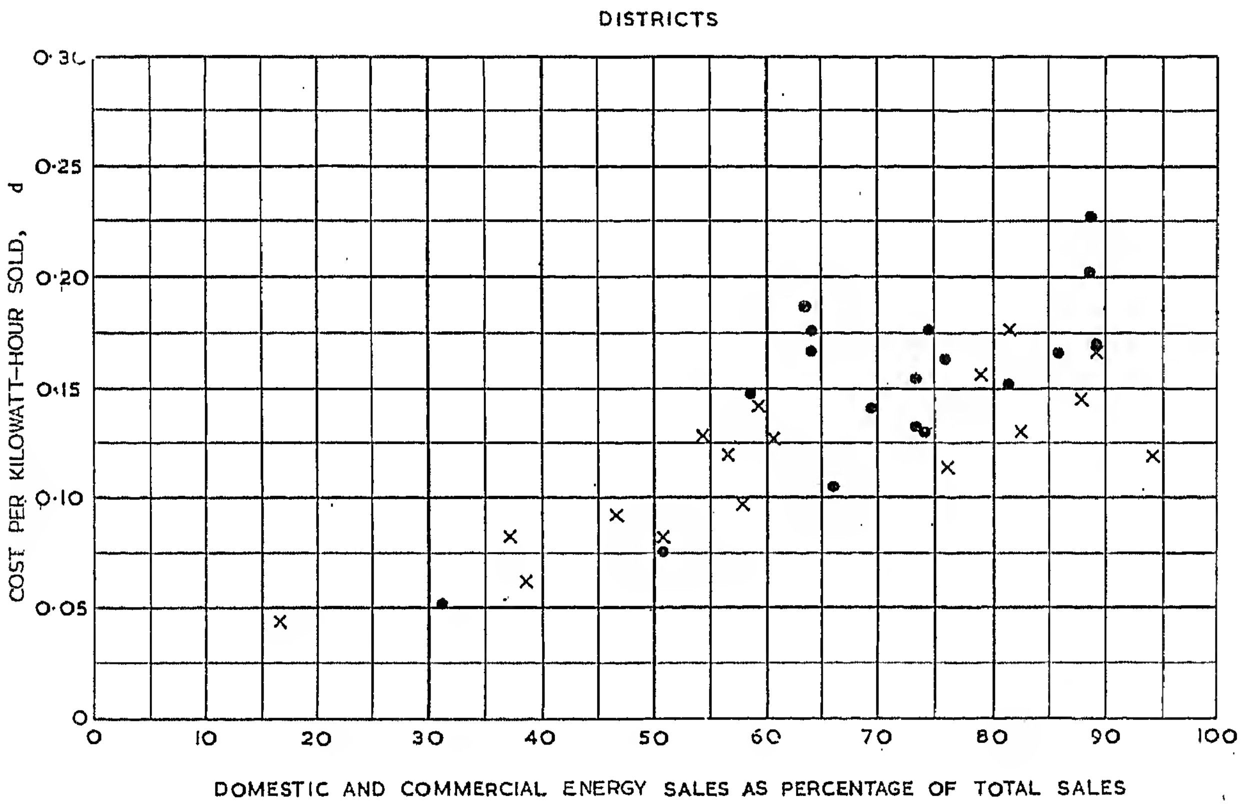

Fig. D.—Administration, consumer service and collection, etc., costs (pence per kilowatt-hour) related to domestic and commercial energy sales as a percentage of total sales. Year: 1953–54.

to bring into account the capital costs because allocation of capital among Districts is of very arbitrary consequence, and undoubtedly there is some interplay between capital costs and administration costs, e.g. as investment in improved plant and machines helps to reduce operating costs.

These detailed difficulties are to be expected in a complex industry supplying a variety of needs under widely differing conditions, and while I do not think that the author's method provides the answer we are all seeking, it does suggest a further valuable line of approach. I hope that with the analysis of further data year by year it will be possible by this and similar means to provide a measure of assessment which will enable the developing industry based on sound consumer service to check its various elements, one against another, in order to achieve an even higher operational efficiency than now obtains.

Mr. T. G. N. Haldane: It occurs to me that perhaps the assumption that the formulae for the consumer-related and other items of cost are linear may not be correct. There seems to be no definite reason why they should be linear, and they may be of some much more complicated character.

Again, the author has stated that his analysis is not complete and has pointed to various factors which might have to be taken into account, and perhaps ought to be, in a final analysis, and so one wonders whether the relatively small discrepancies which have emerged in the analysis might not disappear completely in a final analysis if pursued to the ultimate.

I considered these various criticisms, but I must say that I came back to the view that the author has at least given an approximate yardstick for comparing distribution costs in the various areas, and we are left with the very interesting geographical effect for

which naturally we should like to find some explanation. I think that the geographical effect must be regarded as something real; I do not think it likely that a more detailed analysis would get rid of it.

The author has been careful not to commit himself as to the probable reasons for this geographical effect, but I also notice that the discrepancies as a whole are tending to disappear as time goes on. They were greater in 1951–52 than in 1953–54. It makes one wonder whether this geographical effect, this difference between north and south, is due to something historical, some effect which existed at vesting date but which is gradually disappearing as time goes on. It will not be possible to be sure about that until, with the passage of time, many more figures are available and we see what happens in the years to come. It may be that in 1947 the situation in the south was on the whole less satisfactory than it was further north. The conditions were certainly rather chaotic in the south. Attempts were made to deal with this position prior to 1947, and it was largely the failure of these attempts that led finally to the 1947 Act. The position in the north was not very satisfactory either, but it may have been on the whole slightly better than in the south. I am therefore left with the idea that possibly the Area Boards inherited certain differences between north and south, and that that accounts for the present discrepancy, which is gradually disappearing as time goes on.

If there is anything in that theory, I think that it would be repaying to make a very careful examination of the two Scottish Areas, which come at the extreme of negative discrepancy. In that connection, I should like to ask the author whether figures cannot be obtained also for the North of Scotland. There we have another Area of a very different character, and, if figures can be obtained, it would be useful to see whether his formula works in such conditions.

Like Mr. Melling, I cannot bring myself to accept the author's argument, in Section 3.4, that size has no effect. It seems to me that general knowledge of distribution points in a different direction, and I think that size must have an effect. I am prepared to believe, however, that in comparing the different Areas, all of which are of large dimensions, size does not matter much, because they are on the flat part of the curve when change of size is not very important. If, however, we were comparing a Board's Area with that of one of the small undertakings which existed before 1947, I think that size would be an important factor.

Whatever doubts there may be about the ultimate accuracy of the author's analysis, I think that he has taken a very important step in trying to find a criterion for the comparison of distribution costs, and I sincerely hope that it will inspire others, and the author himself, to pursue this matter further and try to clarify some of the intriguing problems arising from the paper.

Mr. D. P. Sayers: I regard the paper as a piece of mathematical ingenuity which seems to produce more or less the correct answers, but I disagree with the author's comment, in the first paragraph of the Summary and elsewhere in the paper, that such matters as load factor and sales per consumer are largely outside the Board's control. On the contrary, I suggest that these matters reflect very closely the way in which the Boards, and their predecessors, have conducted their business in the past; and I hope that the author will agree with me, for the benefit of the younger members in the industry, that future results will depend very largely on their efforts to-day, and we must not accept a passive attitude to these matters.

In the Introduction we find the dictum that "measurement is the essence of knowledge." I would emphasize that measurement is an essential tool in the creation of knowledge, but not an end in itself. There is too great a tendency nowadays to think that problems can be solved by taking a collection of facts, feeding them into a computer, and accepting the end-product on a plate at the other end. Good engineering requires almost as much art as science, and it is the duty of the engineer not just to accept facts passively, but actively to exert his powers of discernment, discrimination and judgment if those facts are to be applied to get the best results.

Reference is made in Section 2.1 to higher site values justifying special treatment of London. Are site values in London several times those in Birmingham? I do not think so. The implication seems to be that distribution in the city is more expensive than in the rural area, but this is quite contrary to the generally-accepted view.

I am very interested in the results in Tables 3 and 4, and particularly in the allocation of fixed costs between demand-related and consumer-related items. In the national average in Table 3 the consumer-related costs work out at about one-quarter of the fixed costs, or 12% of the total costs of supply, while in Table 4 the figures for the South Eastern Board are higher, at roughly one-half and 15% respectively. In Bellamy's paper presented at the Power Convention last year* there is an analysis for housing estates in which the consumer cost was 12–33% of the total cost of supply; in an analysis of the Birmingham undertaking made in 1945 I estimated a figure of 19% in respect of all l.v. supplies. All these figures hang together fairly well and have an important bearing on tariff construction.

I am interested in the variation of distribution costs from North to South. The same variation has been found in the Divisional costs of generation.

Mr. G. O. McLean: Whilst I admire the author's courage in presenting this paper, since whatever his results he is bound to upset a number of people, I disagree completely with his conclusions. I want to put forward an alternative criterion which I hope to prove is superior to the author's.

It is widely held that management ability when graphed as a frequency distribution would follow a normal curve (in the statistician's sense of the word)—i.e. a Gaussian curve. I felt that distribution efficiency, resulting from management ability, should be examined on that basis. I thought about it a good deal, and as preliminary proof of my theory I took the operating efficiencies of generating stations. The operating efficiency is the ratio of the maximum efficiency attainable according to the cycle of conditions in the steam power station to the thermal efficiency actually obtained.

If we plot as a frequency distribution the operating efficiencies of all the power stations in England, Fig. E shows the result obtained, where (*a*) represents those that ran less than half the number of hours in the year, and (*b*) those that ran the full number of hours. It will be seen that both curves are of the Gaussian type.

If that was true of generating station efficiencies, why should not it be true of distribution operating efficiencies? I therefore tried to obtain a formula which would, when plotted, give me a Gaussian distribution curve. As statisticians know, the simple check for a Gaussian or "normal" curve is to plot cumulative frequencies on probability paper until a straight line is obtained. It is desirable to work with a large "population," so that it was no good considering only the results of the 14 Area Boards. I therefore went to the pre-war Electricity Commissioners' returns and took 1937 as a year without any bias. To obtain a good sample to work with, and a random sample, I took every third undertaking in the alphabetical list and so obtained 194 randomly-selected guinea pigs.

I made several attempts to find a formula for distribution

* Bellamy, D.: "The Development of the Domestic Load at Home and Overseas," *Proceedings of the British Electric Power Convention*, 1954, p. 249.

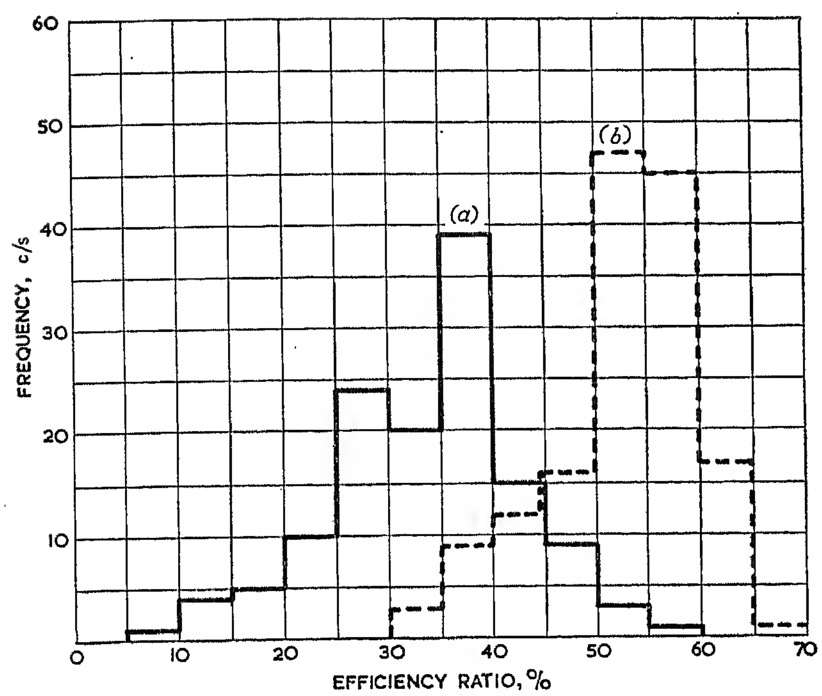

Fig. E.—Steam power stations: 1952–53.

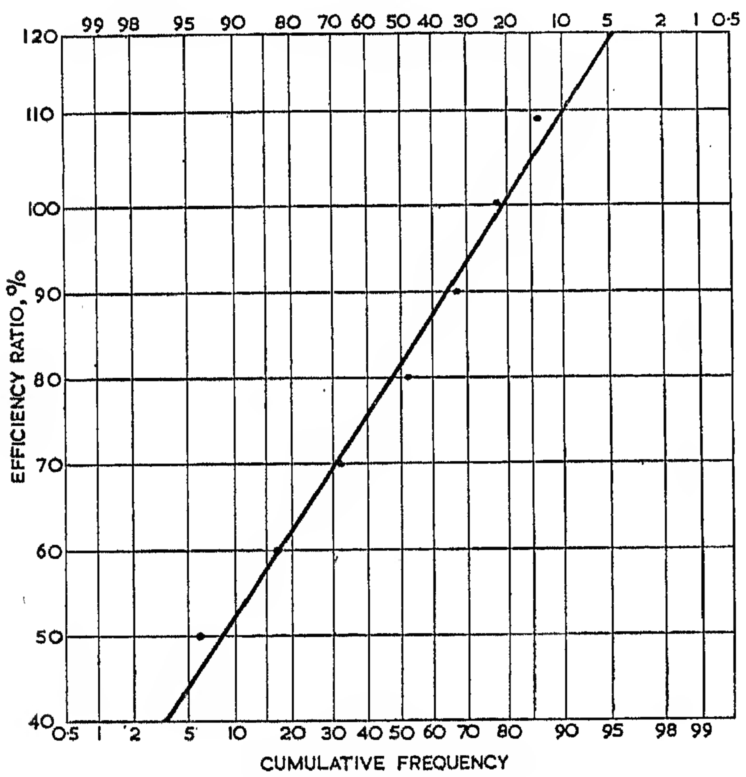

Fig. F.—Efficiency ratios on probability paper.

operation efficiencies which gave a straight line, and Fig. F shows the plots of the 194 undertakings with my final trial formula. I considered that that was near enough to a straight line. (The two end points are a little off the line, but they were explainable.) I therefore accepted the formula which gave me that line.

Fig. G shows how the 194 results show up on a frequency-distribution curve. It will be seen that the curve is very nearly Gaussian. (The missing tail at the front end can be explained by the fact that people who got very bad efficiencies were discharged, while those who obtained high efficiencies were promoted and went to a bigger undertaking.) That result was obtained from this formula:

$$\eta = \frac{P\left(1\cdot 8C + \dfrac{0\cdot 27D + 0\cdot 027I}{240}\right)}{\text{Actual costs (£)}}$$

P is a factor which the author has left out altogether, but Mr. Melling introduced it and proved my point; it is the population factor, and it varies from 1 to 1·2, i.e. by 20%. C is the

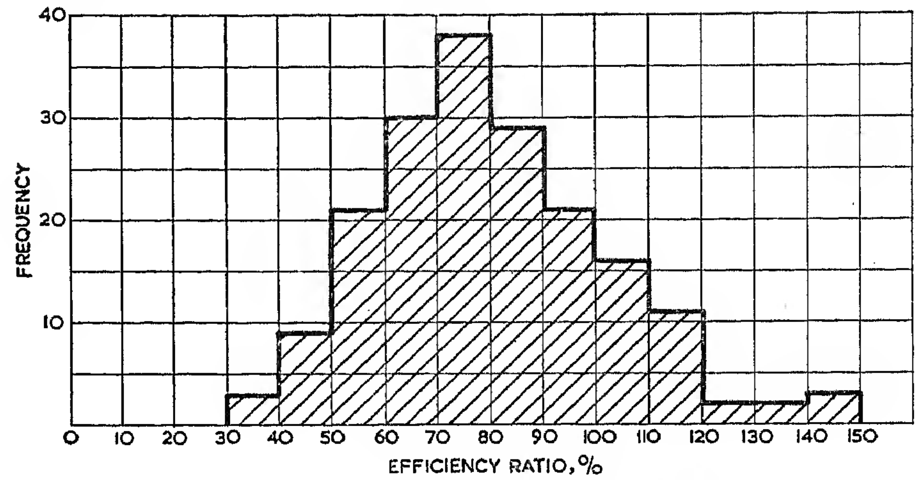

Fig. G.—Frequency chart of 194 efficiency ratios (McLean formula).

number of consumers and D is the number of domestic kilowatt-hours, or non-industrial kilowatt-hours, while I is the industrial kilowatt-hours. I divide the numerator by the actual controllable costs, i.e. distribution plus administration and consumer service and annual capital charges, ignoring energy costs, and so we get the operating efficiency.

Table A shows the results for two years used by the author.

Table A

Comparison of Area Board Efficiency Ratios

Area Board	1951–52			1953–54		
	Ratio	McLean ranking	Bolton ranking	Ratio	McLean ranking	Bolton ranking
	%					
London	51·0	14	11	48·4	14	14
South Eastern ..	59·5	12	13	60·2	11	11
Southern	65·0	7	14	65·6	4	12
South Western ..	65·7	6	12	63·5	5	13
Eastern	68·0	3	10	68·4	3	9
East Midlands ..	64·4	9	8	60·9	8	6
Midlands	64·6	8	4	61·2	7	5
South Wales ..	55·0	13	7	51·9	13	10
Merseyside and North Wales ..	66·6	5	9	63·4	6	8
Yorkshire	64·2	10	3	58·0	12	3
North Eastern ..	61·5	11	6	60·4	10	7
North Western ..	67·6	4	5	60·6	9	4
South East Scotland	83·9	2	2	78·5	1	1
South West Scotland	88·3	1	1	76·3	2	1

I have called the second column the McLean ranking, to compare with the Bolton ranking in the third column. For both years, bell-shaped (Gaussian) curves result, which is correct according to statistical (probability) theory, whereas the author's results have a geographical bias, which is mainly due to energy costs, which are outside the distribution undertaking's control.

Dr. F. T. Chapman: As a member of a Consultative Council it seems to me that the author has set about the writing of the paper in a very logical manner, applying the right principles. He has made a number of arbitrary adjustments which in future years he may desire to alter, and I believe that the results will have to be very carefully interpreted, since he intends to use them to compare the commercial performances of different Boards. I have no doubt that he and the Central Authority will interpret them correctly, but members of Consultative Councils and the public in general might be seriously misled if these figures were issued to them, and I hope that nothing of this kind will be published in the Central Authority's Annual Report for some years to come, because, like Mr. Haldane, I believe that figures

thus calculated would show considerable changes in the next five to ten years.

There are factors which the author has not been able to take into account. I am referring to certain features in the circumstances of the individual Boards which affect the related costs in a somewhat haphazard fashion. Some Boards, for instance, particularly in the South, took over miscellaneous undertakings of which a proportion were under-capitalized while others were inefficient. In the first case, the capital costs—the notional historical costs—are low, but the Boards concerned have taken over with these particular undertakings a future liability for reinforcement and replacement which is likely to put up their capital costs very considerably in the next five or ten years. In the same way, some Boards took over a relatively large proportion of comparatively inefficient undertakings. The Boards concerned got to work on these, reorganized them and reduced their costs, so that in the first years of nationalization they have been able to show a decreasing discrepancy.

Those Boards which have not inherited undertakings where marked improvement in operating costs has been possible may suffer undeservedly from comparisons made as in Table 5 and Fig. 3 of the paper. Hence I deprecate the general publication of such statements until sufficient time has elapsed to ensure that the Boards can be fairly handicapped.

Meanwhile, however, I think a useful purpose can be served if a suitable criterion for comparison can be developed for use by the Boards themselves, and for this the author seems to provide a useful basis in his paper.

Mr. R. F. Richardson: My chief difficulty with the paper is in conceding that the demand-related costs considered should ultimately be used as a criterion in the measurement of the efficiency of the undertaking. Such a cost component is at the mercy of the Board's maximum demand in any particular year, whereas in fact the Board's efforts and its capital expenditure are mainly proportional to the potential demand on the system. As an example, if the calculations relating to the South Eastern Board in Table 4 of the paper are recalculated assuming a load factor of 42% instead of 48%, the discrepancy unaccounted for becomes 4·1 instead of 6·9, and the position in the author's "League table," Table 8, changes considerably. It seems, therefore, that any formula which relies on these fortuitous year-to-year figures in measuring the efficiency of an Area is extremely dangerous.

Table B

CHANGES FOR YEAR 1953–1954 OVER 1952–53

Area	Change in load factor (previous year = 100)	Deviation from average change in load factor	Change in deviation from author's notional cost
	%	%	d. × 10^{-4}
South Eastern	−12·2	−7·3	−389
Southern	−9·0	−4·1	−224
Eastern	−10·5	−5·6	−201
Merseyside and N. Wales	−4·9	0	−119
South Western	−6·6	−1·7	−64
North Eastern	−1·7	+3·2	−11
London	−8·5	−3·6	−7
Midlands	−5·7	−0·8	+2
North Western	+0·2	+5·1	+62
East Midlands	−4·3	+0·6	+80
S. East Scotland	−2·4	+2·5	+120
Yorkshire	−2·3	+2·6	+163
South Wales	−2·7	+2·2	+220
S. West Scotland	+1·3	+6·2	+344
National average	−4·9	—	—

Table B demonstrates the error of the assumption that the load factor of any particular Area varies at the same rate as the national average. In the second column of the Table I have shown for each Board the changes in load factor for 1953–54 compared with those in 1952–53, which is taken as 100. The national average load-factor fell by 4·9% in 1953–54 compared with the previous year. In the third column the deviation from this average change for the South Eastern Board was −7·3% because in that year the Board's load factor fell from 48% to 42%. It is shown at the opposite end of the scale to the South West Scotland Board, which in the same year improved its load factor and had a positive change to plus 6·2%. I think it would be agreed that there is a marked correlation between the deviations from the average change of load factor in column 3 and the "discrepancy" in the author's notional cost in column 4—by which good and bad marks are awarded.

Economies flowing from concentration and intensity of industrialization have been mentioned by previous speakers. I wish only to add that if the fourth-root correction factor (Section 2.4) is applied to the South Wales Board and the Southern Board (incidentally two totally dissimilar Areas) almost the same factor is obtained—an obviously inadequate correction.

I have examined the effect of power factor as suggested by the author (Section 2.7), and find that the power factors of the two Scottish Boards (shown in the paper as having the highest negative discrepancies) tend to be the same as, or even higher than, those of the Boards in the South of England which have the maximum positive discrepancy so that no improvement would appear to result from this correction.

In conclusion, I refer to the curious metamorphosis in Table 8, whereby the Boards with the highest energy costs in the first column become in the final column those with the best performance. This leaves me with the suspicion that for the moment at any rate this is an inadequate basis on which to compare the relative economic efficiencies of the Area Boards, particularly since the quality of consumer service and similar qualitative factors are not taken into account. It is possible, however, that the method suggested could form a basis of comparison for a particular Board from year to year provided the various factors to which I have drawn attention are taken into account.

Mr. G. T. T. Rheam: In producing his yardstick the author has made a number of assumptions and adjustments, but he seems to have taken no account of two important factors, namely (*a*) the ratio of the industrial load to the domestic load, and (*b*) load factor. Although the demand-related costs may be higher for the individual industrial consumer than for the domestic one, the cost of supplying, say, 1 000 kW of load to industry is much less than that entailed in supplying the same load to domestic consumers, and this should be taken into consideration.

If we take the two extreme cases, we find that in the South Eastern Area the industrial load was 40% less than the domestic load, whereas in South Wales the industrial load was six times the domestic load.

Similarly, in 1953–54 the load factor of the South Eastern Area was about 41%, and that of South Wales about 59%. It is not possible to compare properly demand-related costs (which correspond to fixed costs) when they are expressed in pence per kilowatt-hour unless they are first reduced to a common load-factor basis.

Turning to the author's own calculations, he has made a correction for area in order to allow for rural districts. His correction does not seem to be logical, because, in some cases, considerable areas of relatively uninhabited land will be included. A correction based on total mileage of transmission and distribution lines per megawatt, or on population per megawatt

of load, would seem to be better. The population basis would take into account the potential consumers who have still to be supplied, and is therefore, I suggest, the better basis.

These, however, are points of detail. The important question is, Does the author's procedure result in a yardstick by which it is possible to judge accurately the performance of the different Area Boards? Fig. 3 may give a clue to this: from it we see that the rural areas have all substantially improved their performance over the three years, whereas with one exception the position of the industrial areas has deteriorated. Can this be correct, when it is borne in mind that in 1953–54 the load factor of the rural areas deteriorated to a greater extent than did that of the industrial part of the country? Unless there is some logical explanation for the contrary results in the south and in the north, there must be something wrong with the method which the author has deduced.

The consumer—who, after all, is important—is not going to use any yardstick of this sort. He judges the performance of a Board by the level of its tariffs, the reliability of its supply, the service which it gives, the courtesy of the staff, and the avoidance of delay in dealing with inquiries and complaints.

Table C

THE "CRITERION" SIMPLIFIED

N = "Notional" costs (excluding cost of losses).
L_n = "Notional" cost of losses.
A = Actual distribution costs, as defined in the paper, but excluding losses, and taken from annual accounts.
L_a = Actual cost of losses.

$$\text{"Discrepancy"} = \frac{A - N + (L_a = L_n)}{N + L_n}100$$

DETAILED CALCULATION

Notional Costs:

Energy-related Costs:
Common costs, at 0·037d. per kilowatt-hour sold.

Demand-related Costs:
Distribution charges, at 8·23% of £23·6 × $\sqrt[4]{}$(Area/maximum demand)* per kilowatt of maximum demand.
Common costs, at 0·46d. per kilowatt of maximum demand.

Consumer-related Costs:
Distribution Charges, at 8·23% of £15† per consumer (£1·23 per consumer).
Directly consumer-related costs, at £0·975 per consumer.
Common costs, at £0·151 per consumer.
} £2·36 per consumer.

Cost of Losses:
B = Actual cost of net bulk supply.
W_p = Energy purchased.
W_s = Energy sold.

$$r_a = \text{Actual loss ratio, } \frac{W_p - W_s}{W_p}$$

Notional loss ratio, for aggregate of Area Boards, 0·093.

$$\text{"Discrepancy"} = \frac{A - N + (r_a - 0{\cdot}093)B}{N + 0{\cdot}093B}$$

* London, £43·24. † London, £18.

Finally, I disagree entirely with the author's contention that load factor is of no concern to the Board: the improvement of load factor and the reduction of peak load should be one of its main concerns and a measure of its commercial efficiency.

Mr. P. Schiller: One of the merits of the paper is that it brings out the importance of asset-related consumer costs, which used to be neglected—even by the author—until not so very long ago, when only what he now calls "directly consumer-related costs" (metering, billing, etc.) were allocated "per consumer," whereas the whole of the remaining fixed costs were allocated on a kilowatt basis, thus giving misleading cost allocations. The asset-related item is chiefly associated with the l.v. distribution system, and the author's allocation on the basis of total consumers works, because, although up to two-thirds of the total energy sold by some Area Boards is supplied direct from the h.v. system, the consumers concerned represent less than 1% of the total number. Apart from the variation in the proportion of such supplies, there is also the variation in the proportion of underground mains, and one of the reasons why the London Board shows relatively high costs is no doubt that it has practically no overhead lines.

I consider the amount of £15 per consumer used by the author as still too low. Some £10 of it is due to meter and service-connection alone, whereas about 70%—not 30% as in Table 1—of the cost of l.v. mains should be regarded as consumer-related. However, I should like to concentrate on the principal object of the paper, namely to establish a criterion of distribution cost in the form of the discrepancy between the actual costs and computed "notional" costs. Here the author seems to lose himself in a maze of unnecessary complications, by expressing all costs on a per-kilowatt-hour basis.

Table C shows what I think is the gist of the author's method. For the individual items, figures used by him have been taken. The whole calculation of the "discrepancy" is thus very much simplified.

It is also unnecessary and misleading to include the bulk-supply costs, for they are roughly twice as high as the distribution costs with which the paper is concerned, and the relative magnitude of the "discrepancies" is thus reduced to about one-third. The ordinates of Fig. 3 should be, not pence per kilowatt-hour, but the percentage values of the last column of Table 5, which vary between − 21% to + 13·6%, covering a total range of nearly

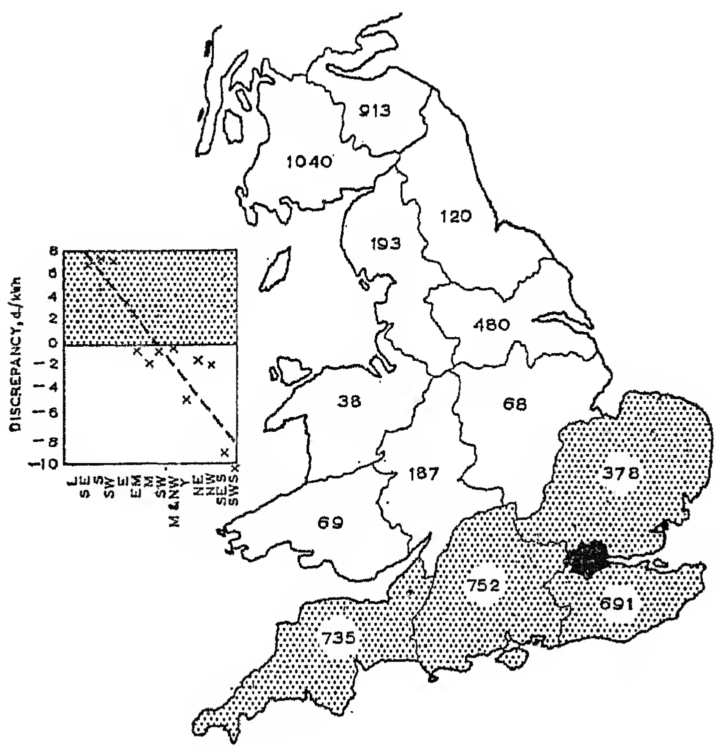

Fig. H.—Geographical distribution of discrepancies, 1951–52.

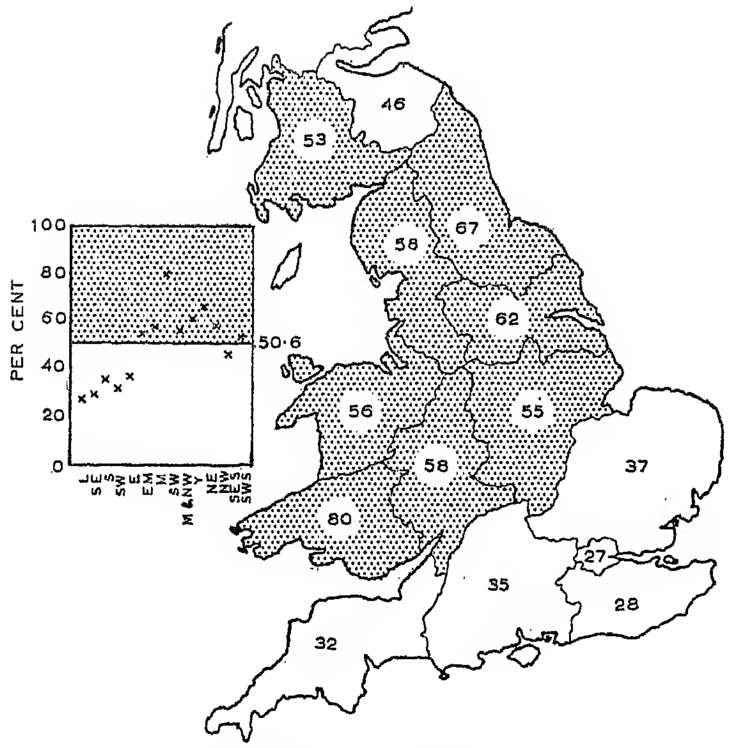

Fig. J.—Geographical variation of the percentage of total consumption taken by industrial consumers.

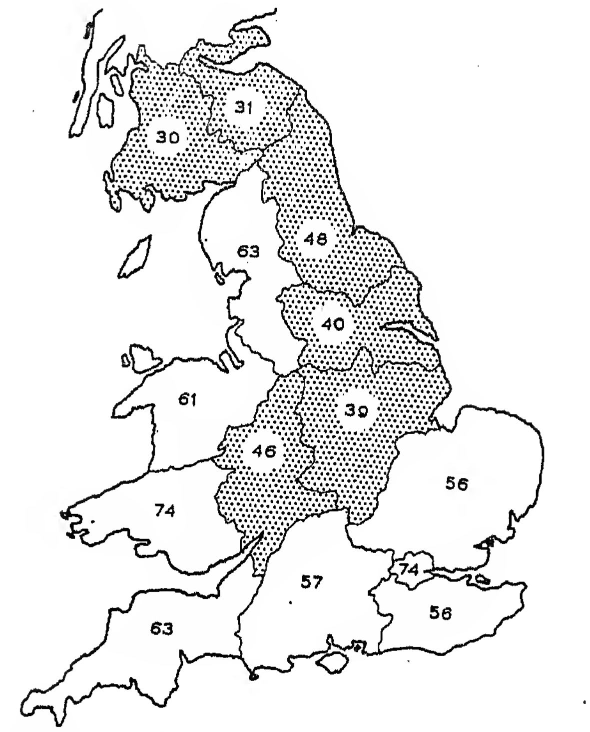

Fig. L.—Geographical distribution of the average service cost per consumer, for the electricity-supply industry.
Average = 54.

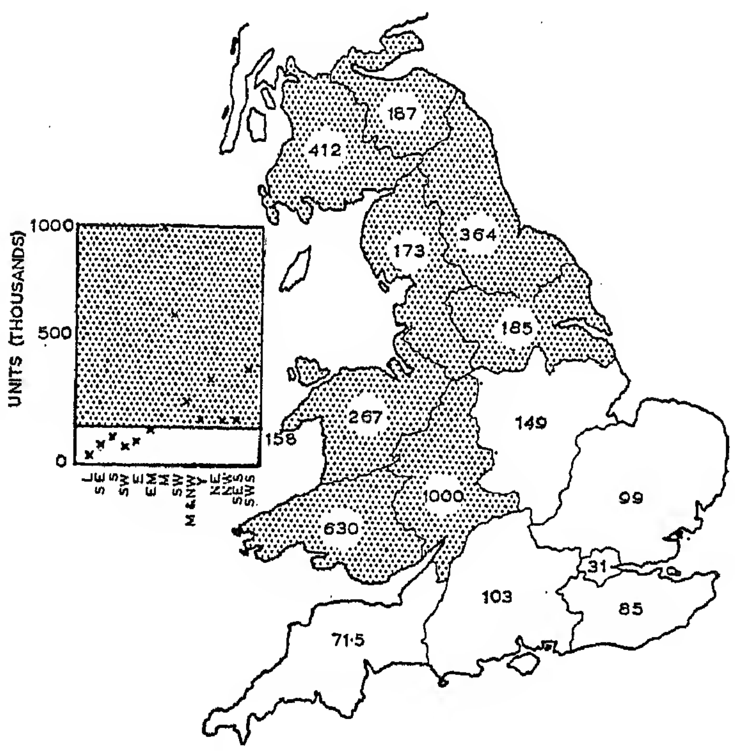

Fig. K.—Geographical distribution of industrial load density.

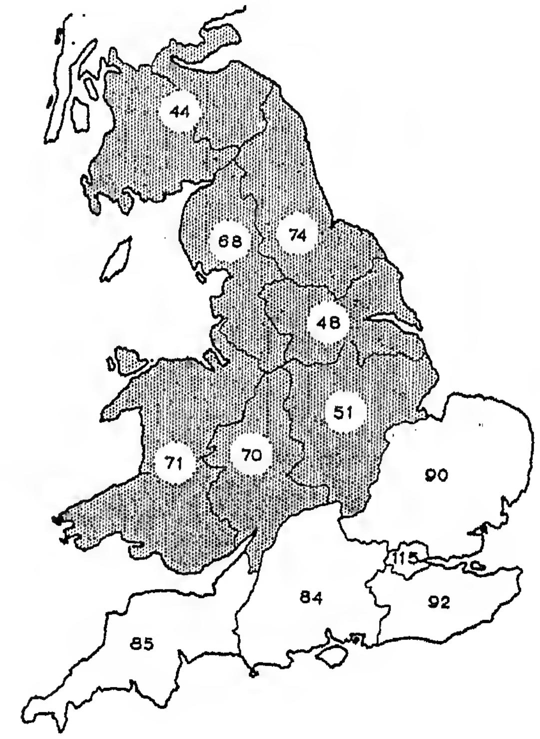

Fig. M.—Geographical distribution of the average service cost per consumer, for the gas-supply industry.

35%. This variation cannot be interpreted as a variation of economic efficiency, and it is difficult to see what the discrepancies do show—except, perhaps, how much still remains to be done to improve the methods of cost analysis and comparison.

They may, however, serve a useful purpose in assessing year-by-year changes in performance, as illustrated in the right-hand portion of Table 8, although I am not quite sure whether the same object could not be achieved more simply by dividing the distribution cost (in the sense of the paper) of each Area Board by the number of kilowatt-hours sold, and considering the year-by-year change, in the individual deviations, or "discrepancies," from the overall average.

Mr. E. J. Whitcher: I doubt the validity of the results of Table 8. Figs. H, J and K illustrate the geographical distribution of the industrial consumption and the average size of industrial consumers' loads, factors already mentioned by previous speakers as providing possible explanations of the discrepancies of Table 8.

Figs. L and M indicate that a similar north/south "cost climate" applies in certain respects to both the electricity and the gas industries, and I think that if these and other factors were properly considered the results would be very different.

The author's formulae and procedure are cumbersome and unpractical because they deal in unreal or notional costs, and the influence of possible action by improved management could not readily be determined.

Lastly, the need for arbitrary weighting by factors as large as 20% "to bring London into the picture" is in itself sufficient to cast doubt on the formulae, and in view of the important issues suggested by the title I hope that members are convinced, as I am, that the author's criterion does not enable Boards to be usefully compared.

Mr. S. F. Osborne: Although the importance of keeping distribution costs as low as possible is appreciated, commercial performance cannot be judged by "Success in keeping distribution costs per kilowatt-hour to the lowest possible figure," particularly if such success were achieved by an increase in the sale of energy at a price insufficiently high to cover all costs.

Load factor and sales per consumer are by no means outside the control of the Boards. Both these—particularly the latter—can be improved by planned development, but as the author makes adjustments for these factors full credit is not given to the Boards which attempt to improve them.

There are two discrepancies in other adjustment factors.

The adjustment for area served should be based on area served and not on authorized area of supply, since some Boards have vast areas which are not at the present time supplied and over which it is probable that supplies will never be justified.

On the question of capital expenditure, figures which have been taken presuppose a uniform accounting system. Although we now have a reasonable measure of uniformity in all Boards this certainly did not exist before vesting day, and book values do not by any means represent the present value of physical assets. Discrepancies arising from this are not eliminated merely because the efficiency is judged on the two-year changes, since some Area Boards have inherited a large number of undertakings with obsolete networks and heavy expenditure in future years; to improve these without securing a corresponding increase in number of consumers or the energy sold would reduce their efficiency according to the author's yardstick.

Mr. R. Baldwin: I should like to refer to some work which was published in 1951 which attempted to find the reason why the southern Boards should have higher costs per kilowatt-hour than those in the north. It was felt that the answer may be in the differing range of ratios of non-industrial to industrial energy sold.

If a graph similar to Fig. 3 is plotted with the Areas set out along the abscissa and the cost per unit (not including bulk-supply charges) scaled vertically, it will be found that there is a sharp dip in costs between the Eastern Area and the East Midlands Area, i.e. on a line between the Severn and the Wash. If, then, a similar diagram is plotted of the Boards' ratios of non-industrial to industrial energy sold it will be seen that the results will follow a broadly similar pattern.

If this factor is considered to be the main reason for the higher costs in the South, it is possible to weight the non-industrial energy with various values and draw a family of curves to study the resultant levelling effect. In the work referred to, the best fit was obtained with a weighted value for non-industrial energy of between five and seven. I was therefore interested to see Mr. McLean's formula, in which he uses a ratio of 10: 1 for these two categories.

In Fig. 3 the author draws a line through his results, but I cannot help feeling that it is misleading. I wonder whether he is clear about it himself, because in Section 4.2 he tends to imply that it is a line drawn between all the points, but in Section 5.3 he says that it is the line of best fit in one particular year. If, however, these results are considered as a family of three sets of figures, and treated as histograms, or even the points linked to form three curves (although this is not mathematically defensible), it will be seen that the author is very far from laying the ghost of this Severn–Wash line.

I feel, in common with previous speakers, that insufficient attention has been given in the paper to differentiation between classes of consumer or load types. Taking the lower of the figures to which I referred earlier for weighting the non-industrial load, namely 5, it is possible to work out the weighting which should be applied to non-industrial and industrial consumers, and this gives a ratio of 18: 1, whereas the author in Section 3.6 of the paper refer to a ratio of 1: 1·5: 3 for domestic, commercial and industrial consumers respectively. Having postulated this ratio, he then expresses the opinion that it is not of very great significance. I should like to ask him whether he has contemplated a ratio such as 18: 1 or, if Mr. McLean's figure is appropriate, considerably higher ratios. It would be most interesting in the report of this meeting to have from the author a study of the effect of this different load ratio between south and north, since it affects his Table of discrepancies.

Mr. F. H. Dennis: With reference to Section 3.4, surely there are still possibilities of further economies of scale. During the last five years the number of consumers per person employed by all Area Boards rose from 106 to 109. At the beginning of that period, there were arrears of repairs and maintenance, reinforcement and replacement owing to lack of materials and depletion of staff during the war years. In the early post-war years, impending nationalization also contributed to this state of affairs. Despite all the additional work which had to be carried out after 1949 there has been an increase in the productivity of labour. It is rather misleading to say that there is no future scope for economies of scale, because I do not think that the supply industry has yet reached that stage of development.

In my opinion the discrepancies discussed in Section 4.2 are largely a measure of the failure of the formula used by the author to estimate the costs in each Area. It seems to me to be a wrong approach to think that it is possible to measure efficiency by such a formula. What we need is a more detailed investigation and the use of more information. For example, the author, as pointed out by previous speakers, has not used all the published information that is available—the length of lines in the Area of each Board, and the proportion of electricity sold to the various consumer classes. It would be better to begin to approach this subject on the lines which Mr. Melling has indicated by examining relationships between particular parts of the distribution organization, instead of trying to compare efficiency by estimating one overall functional figure for each Board.

Mr. J. L. Egginton (*communicated*): For many years distribution engineers have been seeking "a yardstick" to measure distribution costs, and, while qualitative solutions to this problem have been suggested, the method proposed by the author is, I believe, the first quantitative solution and one that comes very near giving the answer which has been so long sought.

There are, however, one or two points in which the author has found it necessary to make approximations and assumptions, and, as the criterion itself is the small difference between two relatively large quantities, such approximations must inherently have a very marked effect upon the discrepancy as calculated.

The author himself has omitted deliberately the effect of power factor. It might not be impossible for him to obtain actual kilo-voltampere demands made by the various Area Boards, and these substituted for the kilowatt demand would automatically take into account the question of power factor.

Another significant point is that the accounts on which he bases his comparison in no case include the cost of 132 kV transmission in the Areas. The effect would be that an Area Board which had a large number of Grid supply points would have an actual distribution cost significantly lower than an Area Board where the number of Grid points was much smaller. It might be possible to take account of this by introducing into the calculation a factor based on "average demand per Grid point" in calculating the "demand-related distribution charge."

In calculating the discrepancy, full credit is allowed for distribution losses. Any Area Board which, by applying Kelvin's law, expends capital to reduce losses will therefore be affected in the following manner. Its actual capital charges will be increased and consequently its annual charges for supplying

electricity will also be increased. On the other hand, its losses will be reduced but the form of calculation will allow it no credit for these reduced losses.

Another factor which is not, and probably cannot, be taken into account is the standard of security of supply provided by each Area Board. The Board which provides the highest standard of security of supply will tend to have the least favourable discrepancy.

I have applied the technique given in the paper for making a comparison between the five Sub-Areas of the Board with which I am associated, and it is interesting to know that the technique can be used for putting the Sub-Areas in an order of merit in the same way as the Areas themselves are put in an order of merit by the author. It is also of interest to note that the more northerly of the Sub-Areas has the highest order of merit, this falling off uniformly from north to south of the Area. While this follows the general conclusions reached by the author for Areas, I feel that the same result occurring in the case of Sub-Areas within a particular Area can only be fortuitous.

In making this calculation it is of interest to note that the actual discrepancies calculated for the Sub-Areas, while being consistent among themselves, are not consistent with the discrepancy calculated for the Area as a whole. This is due to the fact that the annual charges on demand-related assets are calculated by the relationship 1·94 times the fourth root of the area per megawatt. The author has adjusted the constant to ensure that the sum of the annual charges on demand-related assets for each Area Board equals the total for the country taken as a whole. To compare the Sub-Areas within an Area, a different value of the constant would be required.

Mr. L. H. Fuller (*at Brighton*): From a bewildering array of assumptions based on statistics, what I believe may be the correct result emerges—i.e. that a particular Board of the 14 has made greater progress than the others. It is a pity that the author, having got so far, did not go a little further and give us his views on the reason or reasons for such progress.

In consideration of Table 1 it has been asked why the percentage allocation of overhead mains to consumers has been taken as zero, and I fail to see why the figure should differ appreciably from the cable allocation of 30%. I know the author refers to this point in Section 2.2, but no real reason is given: a number of 11 kV and m.v. lines are erected for specific consumers, and are quite definitely not related to demand.

Also, I should have thought that plant and machinery, and the operational land and buildings associated with them, should bear the same percentage. Instead, the Table shows plant and machinery as 15%, whereas the land and buildings which surely must house the plant and machinery are shown as 20%, which seems rather peculiar.

If, now, in the two cases cited above, the larger figure is accepted, according to my rough calculation the total allocation comes to about £22 per consumer instead of £19·3.

To me, the greater mystery about Table 1 is that, having gone to considerable trouble to prepare it, the author appears to ignore the answer, and use instead what appears to be an artificial figure of £15, selected to suit Fig. 2 since it fits it best—although the author admits that the £20 curve is not much worse.

I should imagine that the use of a figure of £22 instead of £15 must make some difference—could it perhaps alter the final order of Board merit?

As to London, whilst not doubting that it is a special case, I think the author should have given more than one reason for relative high cost of fixed assets. He cites high site values, but would not an equally valid reason be the multiplicity of interests before 1948, with resulting parallelism of transmission mains? I remember that Mr. Leach, in his Chairman's Address to the Supply Section in 1948, introduced a striking lantern slide showing transmission mains crossing all over the place.

In Section 3.4 the author deals with common costs, and says that "it is noteworthy in this connection that when two adjacent undertakings are merged into one (or 550 into 15) there is very seldom any material reduction in the total personnel." This may or may not be true—and I take it the author does not really expect more than a marginal difference—but surely under the 1947 Act an initial reduction is not possible? Subsequent reductions are, of course, made by retirements in due course without replacement, but this is masked by new engagements—the distribution industry can hardly expand without some additional men. In addition, transfers have quite often been made which has the same effect. I believe, however, that one of the clues to the mystery of efficiency propounded by the author must be in this very fact—staff ratio. What the numerator or the denominator should be I do not know, but what I will call the geographical cost drift may be partly due to some such factor, doubtless with others. For my own interest, I have been plotting several staff ratios, and have had drawn out that which fits the curve best, as the author did with his £15 per consumer.

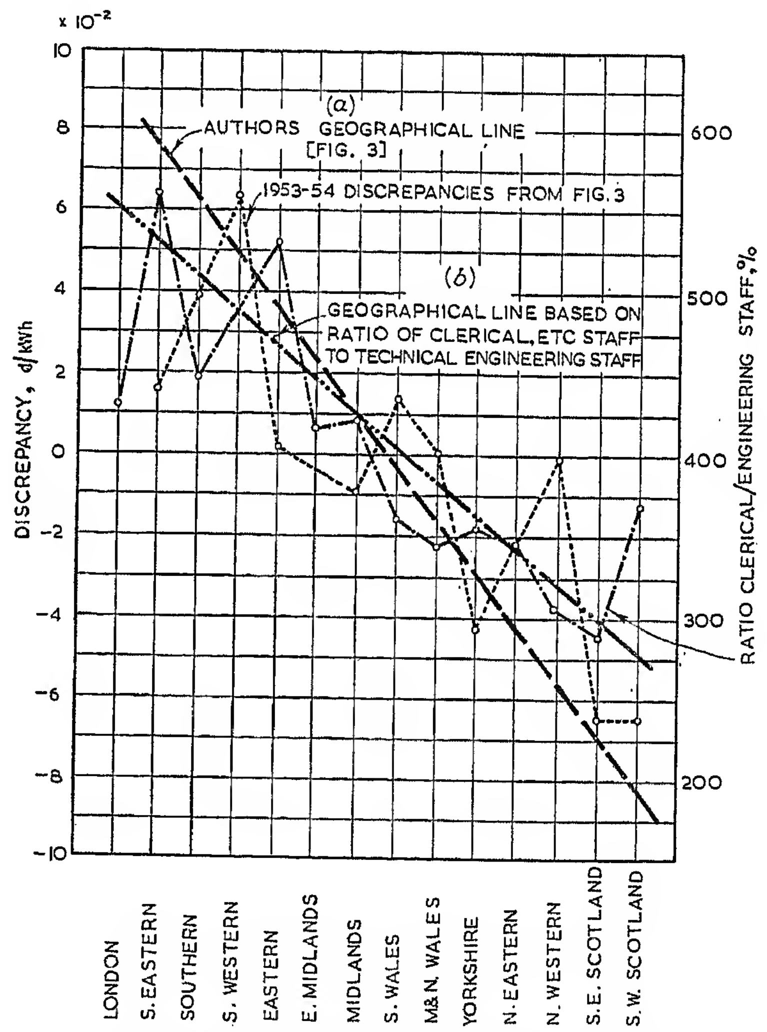

Fig. N.—Discrepancies and the ratios between the relative sizes of the clerical and engineering staffs of the Boards.

Fig. N shows two curves:

(*a*).—This is the author's Fig. 3, with the true curve filled in as well as the "geographical line."

(*b*).—This may come within the author's definition of facetious reasons and is based on the 1953–54 figures taken from Appendix 26 of the sixth B.E.A. Report, and shows the ratio of executive, clerical, accountancy, sales, etc., staff (summarized as "clerical") to the technical engineering staff, with a geographical line drawn as fairly as the author's line. London is well off the curve, but is, of course, ignored.

The similarity of the two curves and the slopes of the two lines are comparable. One conclusion could be that some Boards have too great a non-engineering staff, but it might be worth examination.

Mr. R. W. Langley (*at Brighton*): The author has chosen a most difficult subject and has prepared a paper which he considers gives a reasonable comparison of commercial performance between all Area Boards. It was not an easy paper to read and some of the arguments and theories put forward I found difficult to follow, and there were many with which I could not entirely agree. In Section 3.4 the author states that "broadly speaking if an undertaking grows to twice its size in every respect supplying twice as many kilowatt-hours, having twice as large a maximum demand and serving twice as many consumers spread over double the area, its cost will be twice as great."

This in itself is a very broad statement and has not, I submit, been borne out in practice. To quote statistics from the B.E.A. Report for the past two years, there has been a 10% increase in kilowatt-hours sold, a 16% increase in maximum demand, and a 5% increase in the number of consumers, but the increase in staff has been only 2%. I submit, therefore, that if the increase in staff can be taken as a measure of increased cost, the author's supposition here is not entirely true.

In Section 3.6 the author discusses the differentiation between consumer types. He first of all suggests that some form of weighting should be applied between industrial, commercial and domestic consumers, but then gives a number of reasons why (*a*) this is not possible, and (*b*) it would make very little difference to the results. In this connection I submit that, in view of the difference between Area Boards in the composition of their loads, it is essential to provide some compensation for these differences. As an example, suppose a large paper-mill requires 20 MW of load at a new works within the South Eastern Area (I take the South Eastern Area because it is at the moment predominantly domestic). In addition to the paper-mill a new cement works also required 20 MW. Thus the number of consumers is increased by two and the load is increased by 40 MW. The additional staff which, I submit, would be required to look after the equipment for these two works would not be more than one man-year. If 40 MW of load is distributed to 40 000 consumers, however, assuming 1 kW a.d.d., or, if you like, 20 000 consumers at 2 kW a.d.d., I submit that the cost must inevitably be higher in every respect, and that although the same number of kilowatts of demand is involved, and probably the same number of kilowatt-hours consumed, the staff increase alone would be considerably greater than for the two consumers with 20 MW apiece. In fact, 40 MW of load to domestic consumers constitutes a fair-sized district. The capital outlay on l.v. mains, the losses and the consumer costs for meter reading would all be very much higher than for the two large-power industrial consumers.

The author's figures would therefore be modified in consequence in his three Sections—energy-related, demand-related and consumer-related elements.

To illustrate my point further I have extracted from the 1953–54 B.E.A. Annual Report details of the kilowatt-hour consumption for domestic and industrial consumers in the different Boards' Areas and have plotted them as a ratio of domestic to industrial energy sold on the same curve as the author's Fig. 3. This is reproduced in Fig. O, and it is apparent that a line drawn roughly through these points aligns very closely with the author's discrepancy trend. I appreciate that I have selected a scale which illustrates my point to the most marked degree, but nevertheless I suggest that it is significant that the trend is consistent. I submit, therefore, that one of the sources of error in the author's conclusions is that he has not taken sufficient account of the effect of industrial consumers and the ratio between domestic and industrial consumption.

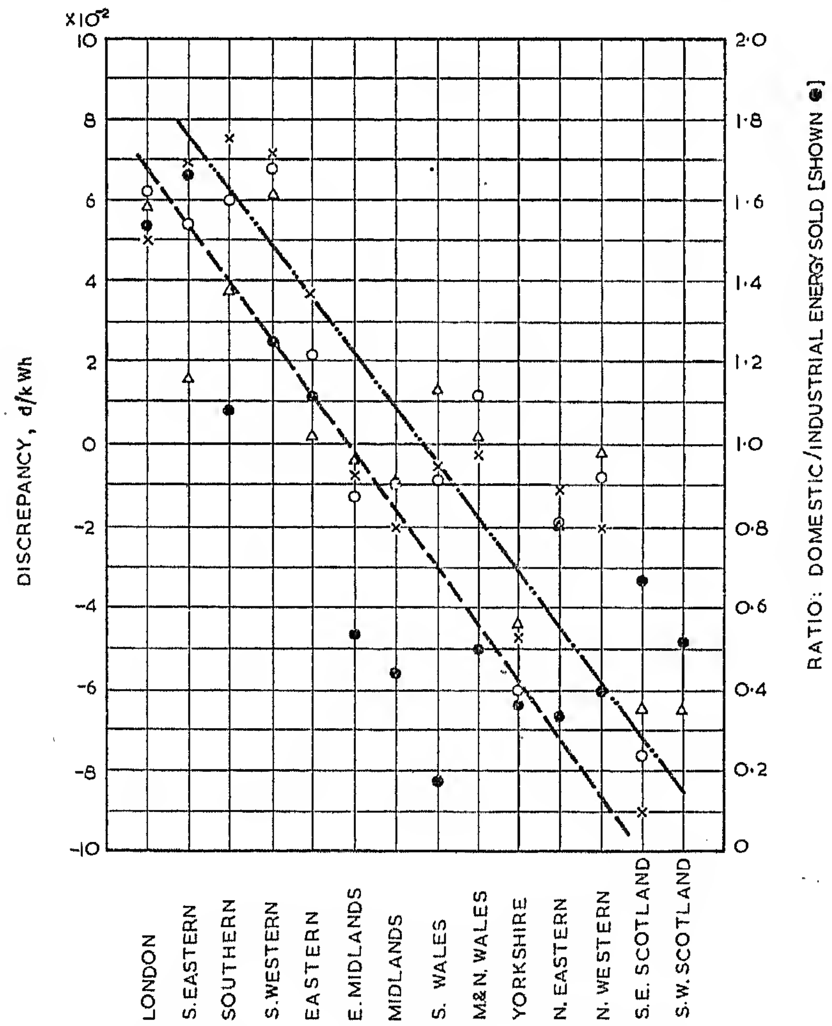

Fig. O.—Discrepancies and the ratios between the domestic and industrial consumptions for the Boards.

Mr. W. Gilchrist (*at Liverpool*): The summary states that "The commercial performance of an Area Board can be judged by its success in keeping the distribution costs per kilowatt-hour down to the lowest possible figure." I suggest that this is completely unrealistic, because a Board has to provide an adequate and efficient distribution system. By this standard, if a Board does not spend money on distribution presumably it will be very efficient—but not in so far as it affects the consumer.

The graphical method of presenting some of the data does not appear to establish reliable conclusions. I am of the opinion, and I think calculation would show, that there is no material difference between Figs. 1 and 2; both indicate that the northern Boards appear to hold a more favourable position than the southern Boards, and this is no doubt due to the preponderance of industrial load in these Areas.

In Table 1 there is no component shown in respect of consumer-related costs for overhead lines, which I feel is a serious omission. With reference to my own Area—of the capital expended in the year 1953–54, one-third was spent on overhead distribution, of which 30–40% was for m.v. mains. I consider that, if capital is to be allocated on the basis suggested by the paper, a similar component for consumer-related allocations should be made for the overhead mains, as is the case with underground mains.

The cost formula in Section 2.5 is most interesting. Here the author uses his academic knowledge on something of a practical problem; he knows the answer A, and the factors D and C, and has assumed a value for the constant K_2; he is left to find K_1. This, he says, is the square, the cube, or the fourth root, and he chooses the latter as this item fits the picture to give the known answer. It is quite simple arithmetic, says the author. He might also have added: "It gives the correct answer A, for the national picture, but by no means that for individual Boards."

This is the most important aspect of the whole paper when we come to the question of discrepancies. Despite the author's

assertion to the contrary, if people believe this is a correct criterion of efficiency, they will say *this* one is better because it is below the datum line, and *that* one worse because it is above it. It is quite wrong to take an overall average for the country in terms of capital, and establish a national formula of costs based on this. To make my point clear, let us look at two Boards—South Eastern and South West Scotland; the capitals used in the notional costs formula are £24 millions and £28 millions respectively, whereas the actual capitals are £32 millions and £21 millions. When the correct capital figures are applied, the picture is entirely different, and the efficiencies of the Boards compare most favourably. The same thing applies to the other Boards' figures.

I feel I cannot accept the paper or its findings as an index of the comparative costs of the Boards, and their efficiencies, either at present or in the future.

Mr. L. C. Grant (*at Liverpool*): One of the most striking statements in the paper is that the performance of an Area Board can be judged by its success in keeping distribution cost per kilowatt-hour down to the lowest possible figure. A lot of this ground has been covered by Mr. Gilchrist in his contribution but there is one further point I would like to make.

I take it that the author means that it is not a question of design of a distribution system, because I think it is more important to take into account the way the system is used; i.e. the use the engineer responsible for it is able to make of his experience, his ability to say that, although his system has such and such a capacity of copper, he can feed a load of x times its copper capacity whereas another engineer can get more. What I am implying is that there must initially be some form of gamble on a distribution system, and whereas the cautious man may add up his individual items of load and perhaps take on twice the copper capacity, another man with more experience and more vision could cater for more. In the course of time full development will come about, but the trouble is that if one waits for it to come about the consumer costs are going to be higher than they should be.

I think also that the high-load-factor consumer does not get the advantage in cost he should have—particularly so since at the other end of the scale tariffs are often weighted so that the low-load consumer pays more than a load-factor calculation warrants.

Mr. E. A. Logan (*at Southampton*): The author has suggested that there are perhaps factors which he has not taken into account in arriving at his final "discrepancies." Does this imply that if all appropriate factors were taken into account the discrepancies would be zero and that all Boards would have an equal result?

There is one major factor over which a Board has no control and which is not in any way a distribution cost, and that is the cost of bulk supply. It seems reasonable to remove the cost of bulk supply from the field of discussion, particularly since this in itself probably contains elements which favour Boards with negative "discrepancies" on the author's scale.

It is unfortunate that by focusing attention on the "discrepancies," which, by their nature, are relatively small, but which tend to label some performances as good compared to others which are thereby indicated as bad, consideration is diverted from the very creditable results achieved as a whole by the electricity supply industry in distributing electricity at substantial and continually decreasing prices in spite of rising capital costs and wages.

In 1938 the overall average cost of distribution was about 0·75d. per kilowatt-hour sold, whereas it is now reduced to about 0·45d. per kilowatt-hour. This is a real achievement in the absolute sense, quite unaffected by marginal adjustments on a hypothetical and highly questionable basis.

Mr. E. A. Hammond also contributed to the discussion at Southampton.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. D. J. Bolton (*in reply*): For brevity the general term "index" is used to indicate the results of my calculations. Few speakers have referred to what I regard as probably the major usefulness of my index, i.e. for making year-by-year comparisons within a single Board. In the absence of criticisms, one can only assume that this portion of the work commands general acceptance.

Mr. Melling.—It is true that a Board's usefulness does not consist merely in the sale of energy and power, and that the imponderables of the service (*a*)–(*e*) largely defy measurement. He would be a bold man, however, who would assert that the Boards differ radically between themselves in what they provide under these heads, and a still bolder man who would particularize thereon. I agree that my correction for load density is imperfect through taking no account of the different kinds of rural territory: this will not, of course, affect year-to-year comparisons. The climatic effect on the yearly comparisons can be overcome in the manner mentioned in my reply to Mr. Richardson.

The balance between industrial and non-industrial consumption is largely paralleled by the balance between high and low consumption per consumer, and the latter is compensated for in my index. The reason why industrial loads incur a lower cost per kilowatt-hour sold is largely because they make a lower proportional use of the distribution assets. By treating a substantial proportion of the assets as consumer-related, the necessary compensation is obtained. This is confirmed by Mr. Melling's own curves. In the two Figures for the separate Boards there is almost no correlation between distribution cost and non-industrial consumption ratio (Fig. A), but there is considerable correlation between consumer service, metering, etc. cost and this same ratio (Fig. B). Evidently the difference in cost per kilowatt-hour between industrial and non-industrial loads is very closely linked with the difference due to selling more or less energy per consumer and is covered in my index by the consumer-cost allocation.

Mr. Haldane.—It is true that any one of the cost components could vary in a non-linear manner, but as the total of them all does vary linearly (showing no "economies of scale"), the inference is that the components do the same. Moreover, the character of electricity-supply assets, built up largely of individual uniformly-priced components, suggests that at least the asset-related costs will have a long-term linear relationship. Mr. Haldane has propounded a very plausible explanation both of the relative discrepancies between Boards and of their annual trend, and it will be interesting to see whether future figures bear him out. The North of Scotland Board could be brought into the first year's comparison by means of a more or less arbitrary handicap like that for the London Board, only more complicated. In subsequent years the index would be valid and I believe useful.

Mr. Sayers.—In my Summary I should perhaps have said that load factor and sales per consumer are largely outside a Board's *immediate* control, and outside the proper scope of correction in my index. This is designed only to measure relative economic merit and not merit in any wider sense, i.e. merit in distributing at the lowest cost within the existing framework. Whatever

efforts are made, both strenuous and meritorious, nothing can alter the fact that at the moment certain Boards have more kilowatts of maximum demand and more consumers per unit of energy than others, and to that extent their cost per kilowatt-hour cannot help being higher. They are being asked to supply a more expensive article, high-powered energy, and while they may in the long run succeed in persuading the consumer to take a more economical supply, in the short run they must supply what is asked for and charge accordingly. My index allows for this and indicates no positive discrepancy when costs are high due to a low load-factor.

Mr. Sayers asks whether site values are so much higher in London than in Birmingham. I would have thought that Birmingham was not so different from other large provincial towns, and that most Boards are alike in having one or two towns with a few acres of very high site values. London is unique in consisting of almost nothing else, and including some of the highest in the world. He quotes some useful comparison figures which, as he says, are very broadly in agreement with my own.

Mr. McLean.—The analogy between generation efficiency and distribution economy may be misleading. In a power station both input and output are physically measurable quantities and the efficiency can be a true ratio between two energies. Distribution economy is a more intangible quantity, since the output is difficult to measure, and the result can at best measure only comparative economy. The consequence is that Mr. McLean arrives at an empirical formula for distribution "efficiency" whose constants are arbitrary and which might perfectly well produce an efficiency of 200%. My formula has the advantage that the output is built up logically from the main electrical functions; on the other hand, it is designed only for, and limited to, the particular purpose of comparing 14 authorities (all fairly large). Mr. McLean's formula is designed for and developed from quite a different situation—the comparison of 194 authorities of widely different magnitudes, and its only proof is that it gives a Gaussian distribution for its results. I do not regard this proof as adequate, and the formula lacks a rational basis. Thus, while certain costs are definitely demand-related, there is no corresponding element in the numerator of the fraction. When applied to the Boards the results show no geographical bias, although almost all other speakers seem to agree that such an element exists. The geographical bias of my index is not due to energy costs, which are compensated for on a factual basis.

Dr. Chapman.—There were certainly wide differences between the Boards regarding the degree of capitalization in the vested undertakings, and using my index as a starting point, some explanation on these lines might lead to useful action. But until a numerical index of some kind is available, there is nothing to explain.

Mr. Richardson makes a valid point that, while my index compensates for the load factor of the particular year, many of the demand-related costs do not fluctuate in this immediate manner. This will not affect the average position of the Boards over the years, nor their long-term trends, but will have the effect of exaggerating the year-to-year fluctuations. The effect, however, is less than might appear, because it applies only to the distribution portion of the demand-related component. The bulk-supply portion is based (correctly) on the particular year's load factor and reflects the Boards' actual payments.

In the light of this criticism, the figures of the paper have been recalculated, and the distribution demand-related element of the notional cost has been based, not on that year's load factor, but on the Board's average load factor over the last three years. The new points, whilst preserving the same general relationship as between Boards, show somewhat smaller annual changes and are to this extent more realistic. The contrasts in Table 8 arise because discrepancies are compared with changes. All that has happened is that, in general, discrepancies have decreased.

Mr. Rheam.—My index allows directly for load factor, but only indirectly for the ratio of industrial to domestic consumers. The suggested weighting for load density, namely population per megawatt, would not compensate for differences of terrain, which was the object of my weighting. The 3-year changes in the north and south Boards can be explained in terms of the general trend of decreasing discrepancies.

Mr. Schiller.—While accepting the numerical values of Mr. Schiller's restatement, I do not agree that it is an improvement in presentation. I included bulk-supply costs, first because I wished to account for the whole selling price by building up all the separate components thereof, and secondly, because the cost of losses, although part of distribution, must be calculated from the bulk-supply figures. The simplified index proposed by him would take no account of each Board's yearly changes in electrical characteristics, such as sales per kilowatt and per consumer.

Mr. Whitcher.—The purpose of the London weighting was to bring this Board into line for the first year so that its progress in subsequent years could be plotted and compared with that of other Boards.

Mr. Osborne.—It is true that my index takes no account of charges, but one must assume that in the long run receipts will cover costs. It is also true that, owing to accounting differences in the vested undertakings, the different Boards' book values are not a uniform indication of the size of their assets. This, however, makes no difference to my index. The separate Boards' book values were used only in finding a law for the consumer-related portion, and do not enter into the subsequent calculations.

Mr. Baldwin.—The weighting comparisons made do not relate to the same thing, and an overall weighting of any kind would be unsatisfactory, because two different factors are involved, namely, consumer cost and industrial versus non-industrial distribution cost. The cost must be broken down into components, not just smoothed over by a weighting ratio (e.g. 18: 1) so great as to swamp all the finer computations.

Mr. Dennis.—Unquestionably there are "economies of time-duration" but this is not quite the same thing as "economies of scale." All that is necessary for the validity of my index is that at any one moment, and within the size range covered by the fourteen Boards, there is no overriding advantage in a big Board over a small Board. A plot of discrepancies against the Board size shows no size correlation whatever, nor has any speaker claimed that such exists.

Mr. Egginton.—I agree that Boards having a large number of bulk-supply points in proportion to their demand have a cost advantage for which my index does not compensate, and had the figures been generally available, an adjustment such as he proposes would have been included. Degree of security is another of the imponderables whose differences might help to explain the discrepancies. I am very interested in the application to Sub-Areas, and I feel that year-by-year recalculations cannot help but be of value in showing the results of changes in re-equipment, reorganization, etc.

Mr. Fuller.—The reason for using a different percentage allocation to consumers for the buildings from that for the plant contained therein is that a bigger proportion of the plant cost is kilowatt-related. A recalculation on the basis of £20 per consumer results in only small numerical changes and almost no alteration in the merit order. Admittedly there are other reasons besides site values for London's special position, but the reasons are irrelevant. What matters is that an adjustment has to be made so as to provide a useful basis for subsequent-year plotting. Inevitably, my paper starts a number of hares, and of the

suggestions made to date, Mr. Fuller's "staff ratio" offers the finest prospect of a day's hunting in what is very sporting country.

Mr. Langley.—The changes which occur in the course of years do not upset the size proportionality assumed in the calculations. The cost differences between distributing a given amount of energy to a few consumers and to many can be equally well covered on the basis of a consumer cost as on the basis of an adjustment for the ratio of industrial to non-industrial sales.

Mr. Gilchrist.—I agree that the consumer allocation for distribution mains is very much an open question, but the adjustments suggested would not bring the consumer allocation above about £20, the effect of which has already been noted. The purpose of my index is not to assign praise or blame but to serve as the starting-point of an investigation as to causes. I agree with the facts of his penultimate paragraph, but I think they are best used in explaining the discrepancy rather than in calculating it.

Mr. Grant.—One reason for the discrepancies is doubtless that distribution engineers in some areas have been more successful than elsewhere in estimating the chances and thus achieving the most economical distribution system.

Mr. Logan.—My index admittedly measures only relative progress and discounts the very real absolute progress Mr. Logan mentions. For that reason it is likely to be more useful because it wastes no time in self-congratulation, but by a purely comparative method seeks to indicate where there is probable scope for still further improvement.

DISCUSSION ON "THE ECONOMICS OF LOW-VOLTAGE ELECTRICITY SUPPLIES TO NEW HOUSING ESTATES"*

Mr. W. A. Carne (*communicated*): I suggest that the author would be on firmer ground if he were to base his plea for planned distribution on the grounds that it is the duty of Electricity Boards to "promote the use of all economical methods of . . . distributing electricity" instead of making a totally unwarranted and unsubstantiated assumption that "domestic electricity supplies are heavily subsidized by other business of the Electricity Boards."

The amount of post-war housing so far completed is relatively insignificant when compared with existing domestic supplies, which have increased in appliance saturation three- or even four-fold since 1939 with insignificant expenditure on distribution.

Continuous records taken locally on three large areas of pre-1939 housing supplied by a total of 17 substations shows that on mild days during this winter the daily load-factor has varied between 50% and 59·8%, and that during three successive days of the coldest spell so far encountered this winter the load factors were 61·9%, 60·6% and 58·9%.

* COPLAND, F. G.: Paper No 1236 S, July, 1952 (see 99, Part I, p. 95).

The domestic load as a whole should have no difficulty in carrying the burden of new housing for many years to come.

Industrial and commercial classes of consumer both have their uneconomic supplies to support, namely the modern single-shift factory with canteen and the vast modern schools with kitchens, both of which produce load curves shaped like a church with a tall steeple with lightning conductor to attract the full force of the bulk-supply tariff.

Mr. F. G. Copland (*in reply*): The statement to which Mr. Carne objects was, and is, based on field and published data derived from several independent sources which produce closely similar results.

In assessing load economics, the only load factor of significance is that related to the demand at the time of the system maximum demand on which payment is made, and the annual consumption.

A complete demonstration of the accuracy of the statement made is not possible here, and I can merely reiterate that whilst Mr. Carne may hold the contrary opinion, the position has not materially altered in the interval since the paper was written.

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Paper No. 1794 M
Feb. 1955

IRON LOSSES AT HIGH MAGNETIC FLUX DENSITIES IN ELECTRICAL SHEET STEELS

By Professor F. BRAILSFORD, Ph.D., Wh.Sch., Member, and C. G. BRADSHAW, Ph.D., B.Eng., Graduate

(The paper was first received 22nd September, and in revised form 11th December, 1954. It was published in February, 1955, and was read before the MEASUREMENTS SECTION *1st March,* 1955.)

SUMMARY

The paper describes a thermal method of measuring iron losses in sheet materials which may be used at any flux density. The method is used to measure the total iron losses at 50c/s in a number of silicon-iron materials and in one sample of cobalt iron up to an approximate induction of $2\cdot4\,Wb/m^2$. The hysteresis component of the loss, obtained by subtracting the calculated eddy-current loss, is found in all cases to reach a saturation value at high densities. Empirical formulae are given which aim at giving the loss at high inductions from a knowledge only of the losses at lower densities.

LIST OF SYMBOLS

B = Magnetic flux density.
B_{max} = Amplitude of magnetic flux density.
H = Magnetic field strength.
H_{max} = Amplitude of magnetic field strength.
M = Intensity of magnetization.
M_{max} = Amplitude of intensity of magnetization.
M_s = Saturation value of intensity of magnetization.
$m = M_{max}/M_s$.
p_h = Specific dynamic hysteresis loss.
p_s = Saturation value of p_h.
$p = p_h/p_s$.
a, a', b, b' = Coefficients.
n = An exponent.
μ_0 = Absolute permeability of free space, or primary magnetic constant ($= 4\pi \times 10^{-7}$ henry/metre).

(1) INTRODUCTION

The iron losses in thin magnetic laminations with high alternating inductions are of special interest in rotating electrical machines. The tooth flux densities in motor and generator punchings may often greatly exceed $2\cdot0\,Wb/m^2$ (20 kilogauss), but owing to difficulties in measurement, iron-loss data have not hitherto been available for inductions greater than about $1\cdot8\,Wb/m^2$. Moreover, extrapolation of existing iron-loss curves to higher flux densities has not been satisfactory, since the shape of the curves in this upper region was not known.

Difficulty in the measurement of iron losses using a dynamometer or electrostatic wattmeter begins when the flux density (in the case, for example, of a dynamo iron) approaches $1\cdot5\,Wb/m^2$, although this method has been used[1,2] up to $1\cdot8\,Wb/m^2$. At these inductions the magnetizing current increases very rapidly with increasing flux density. It becomes difficult to avoid overheating in the magnetizing circuit and the power factor falls to very low lagging values, e.g. 0·02 at $1\cdot8\,Wb/m^2$. Moreover, severe waveform distortion must inherently appear in either the current or the flux waveforms; in fact, at high flux densities neither the current nor the e.m.f. induced by the flux in the specimen can be kept free from harmonics. Because of the low power factors and the presence of harmonics, small phase-angle defects in the wattmeter and its associated equipment may introduce very serious errors in the wattmeter observations. Bridge and potentiometer methods are similarly affected, waveform distortion being a particularly serious source of trouble.[3] Cormack,[4] however, has published results for a silicon-iron material with inductions up to $2\cdot0\,Wb/m^2$, but the few scattered experimental points obtained at the higher densities enabled no conclusion to be drawn about the shape of the upper part of the iron-loss curve.

Hysteresis loss has been determined from the areas of hysteresis loops[1] and also[5] by direct measurement of the mean torque required to rotate disc specimens in a steady magnetic field. $1\cdot85\,Wb/m^2$ is about the upper limit of induction for satisfactory measurements in these cases.

Calorimetric methods of measuring iron loss have been used,[6] at least up to $1\cdot5\,Wb/m^2$, but the problem of thermal interference from the copper losses in the magnetizing winding may become acute at high flux densities. One published method,[7] however, would surmount this difficulty, and in the present investigation it has been similarly overcome. To obtain successive points on the iron-loss curve by the present method the magnetizing coil need be energized only for a few seconds at a time. Hence, when the highest flux densities in the specimen are reached the copper may be very heavily overloaded intermittently without overheating or interference with the measurements.

In this investigation, iron-loss measurements have been made by a novel method on a number of materials at 50c/s and at flux densities up to about $2\cdot4\,Wb/m^2$ and the shape of the iron-loss curves well into the region of magnetic saturation has been established.

(2) METHOD OF MEASUREMENT

(2.1) Principle

The principle of the method is shown in Fig. 1. The magnetic strip specimen A carries an alternating magnetic flux Φ when the magnetizing winding E is energized. C is a non-ferromagnetic strip of resistance material which may be heated by an alternating current I. Thermo-junctions J_a and J_c, attached respectively to the two strips are connected in series opposition to the detector D. Closing switch S causes the specimen to be heated by the iron losses, and the guard strip is simultaneously heated by the current flowing in it. If, for a given flux Φ, I is pre-adjusted by trial until on initially closing S there is no deflection of the detector, the rates of rise of temperature of the two strips will be the same. On the assumption of no loss of heat from either strip and materials of the same specific heat, the specific iron loss in the specimen is equal to the rate of heating, for example in watts per kilogramme, in the resistance material C: or if the specific heat of A is n times that of C, the iron loss is n times this amount. Since the power in watts per kilogramme supplied to the guard strip is easily measured, the iron loss is also known if the ratio between the specific heats

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Dr. Bradshaw was formerly at University College, London, and is now at the Signals Research and Development Establishment.

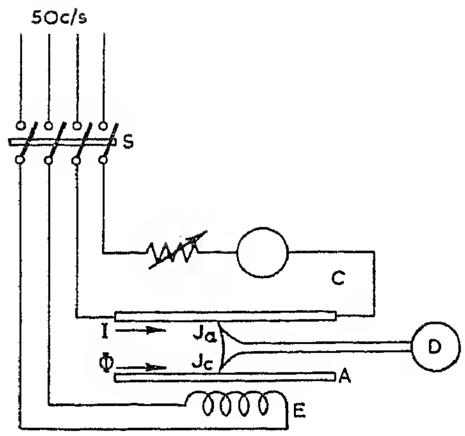

Fig. 1.—Illustrating principle of method.

A. Specimen.
C. Resistance material.
E. Magnetizing winding.
J_a, J_c Thermo-junctions in opposition.

of the two materials is known. If this ratio is not known it may, in principle, be found by a second experiment in which the specimen is not heated by the iron losses but both strips are simultaneously heated by separate currents. This method of direct calibration was, in fact, used in the present investigation, since the specific heats of the different materials were not known with certainty.[8] Moreover, direct calibration eliminates possible errors arising from minor departures from ideal conditions due, for example, to the presence of B and H coils or a small difference in the thermal capacities of the two thermo-junctions.

(2.2) Magnetic Core

Thermal considerations referred to in Section 2.5 suggested a total working length of the strip specimen of 7cm and a convenient width of specimen was 3cm. These dimensions then determined the size and proportions of the magnetic core shown in Fig. 2. The magnetizing coil was wound on a Bakelite former

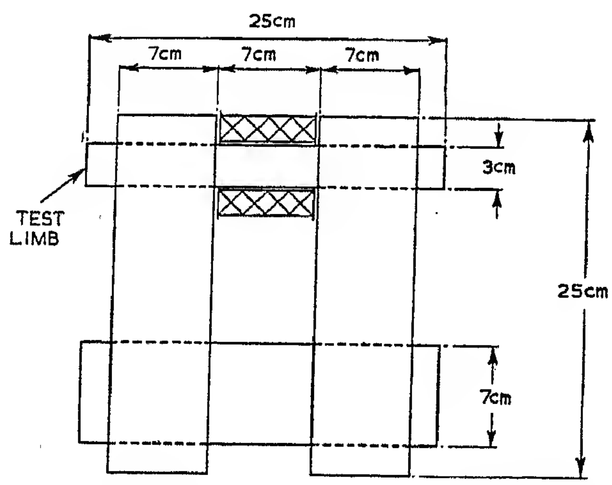

Fig. 2.—Test limb, yoke punchings and magnetizing coil.
Dimensions in centimetres.

about 7cm long with inside dimensions 3·2cm × 3·2cm. Although the specimen itself consisted of a single central strip, the test limb was built up from a packet of strips of the same material, so that the overall cross-section of the limb was 3cm × 3cm. Putting as much iron as possible inside the magnetizing winding cuts down the proportion of air flux in the coil and so helps to reduce the inevitable flux-waveform distortion at high densities. With the same object, it is advisable that the specimen and the remainder of the test limb should not be magnetically dissimilar. Strips 25cm × 3cm were used for this limb in each case, and the yoke was completed by overlapping 25cm × 7cm pieces of 0·018in dynamo iron. The

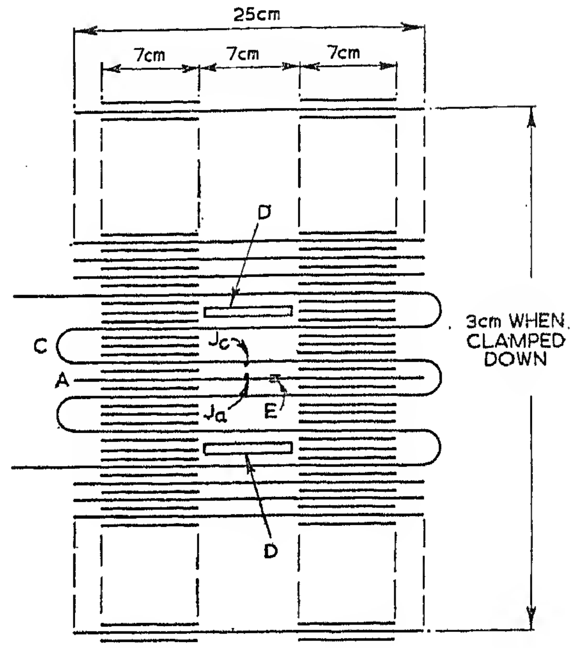

Fig. 3.—End-view of test limb expanded in vertical direction to show specimen A and arrangement of guard strip C.

A. Specimen.
C. Resistance material.
D. H coil.
E. B coil.

method of assembly of the pieces is shown in Fig. 2 and also in the end-view, Fig. 3. The iron cross-section in the three yokes is therefore not less than 7/3 times that of the test limb, so that if, for example, the flux density in the specimen is $2{\cdot}4\,\mathrm{Wb/m^2}$, that in the yokes will be not more than $1{\cdot}0\,\mathrm{Wb/m^2}$. Almost the whole of the m.m.f. of the magnetizing winding is therefore absorbed in the 7cm length of the test limb. In fact, at high flux densities the coil and the core inside it may be regarded as a 7cm section of an infinitely long solenoid, and preliminary measurements confirmed that there was a negligible variation of flux density along the test length of the specimen.

The specimen under test is shown at A in Fig. 3. This was sandwiched between layers of the nichrome guard strip C which was interleaved with the yoke punchings in the manner shown and insulated from them with empire cloth. The thermo-junctions of 30s.w.g. copper and 36s.w.g. constantan were very lightly soldered at the midpoint of the limb at J_a and J_c.

(2.3) Magnetic Field and Flux Measurements

Each specimen was wound with a B coil shown at E in Fig. 3, using 20 turns on the thicker materials and 40 turns on the others. Two H coils on Bakelite formers 0·030in thick were inserted in the test limb, as shown at D. One of these coils had 100 turns and the second, or compensating, coil had separate windings of 1, 2, 3, 5 and 9 turns; 30 s.w.g. copper wire was used for all these coils.

Measurements of magnetic field strength and flux density were made using a reflecting galvanometer and synchronous commutator of the type described by Dannatt and Holt.[9] Thus complete waveforms of B and H could be plotted when required.

For the thin specimens under investigation the cross-sectional area of the B coil was at least twice that of the iron itself. For high field strengths the air flux in this coil is therefore a substantial amount; for example, if H_{max} is 2kA/cm the air flux is more than 10% of the total flux in the coil with the present materials. To obtain the true flux densities in the iron in the saturation region, an accurate air-flux correction must thus be applied. This correction cannot be computed with certainty for thin specimens, since the mean area of the B coil cannot, in practice, be accurately measured. However, magnetic saturation is very nearly attained in iron and silicon-iron when the field

strength reaches, say, 800amp/cm (1 000 oersted), so that $M_{max} = (B - \mu_0 H)_{max}$* remains approximately constant with $H_{max} > 800$amp/cm. The air-flux correction was then made automatically by connecting the compensating H coil in opposition to the B coil and, in successive trials, varying the number of H-coil turns until, on increasing H_{max} from 800amp/cm upwards, no increase in deflection of the flux-measuring galvanometer occurred. The readings then gave the true values of the intensity of magnetization in the specimen, $(B - \mu_0 H)$ or M. At high flux densities B and H have their maximum amplitudes at the same instant, so that $B_{max} = \mu_0 H_{max} + M_{max}$. H_{max} was obtainable from the main H coil and hence B_{max} could also be determined, as could the waveform of B if required.

(2.4) The Detector

A d.c. detector of comparatively high sensitivity is required. An iron loss of 1watt/kg, for example, in an iron specimen produces an initial rate of rise of temperature of about 0·002°C/sec or a rise of temperature of about 0·008°C if the supply switches are closed for 4sec. With a thermocouple sensitivity of 40μV/°C the e.m.f. in each junction would then be about 0·3μV. To detect a difference in the rates of rise of temperature of the specimen and the guard strip of, say, 0·5% when the loss is 1 watt/kg and the interval is 4sec, the voltage available is then 0·0015μV; if this voltage gives an observable deflection on the scale of 1mm, the required detector sensitivity is about 700mm/μV.

To obtain this degree of sensitivity while using robust galvanometers, the galvanometer-amplifier system described by Preston[10] was employed, with some minor modifications. The circuit used in the present case is shown in Fig. 4, and the theory has been

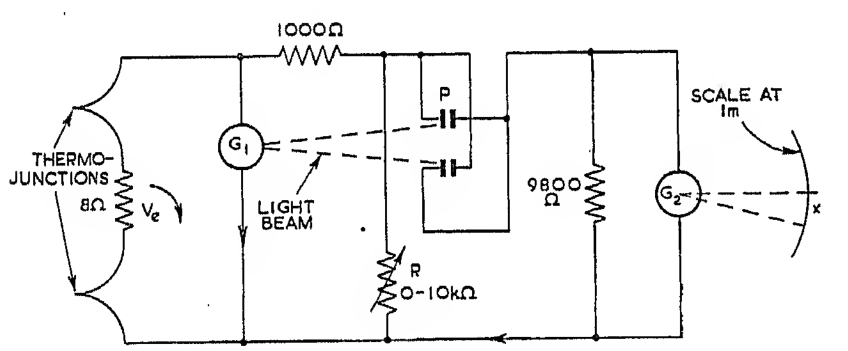

Fig. 4.—Circuit of galvanometer amplifier.

Primary galvanometer G_1 : 21 Ω, 2·2 sec period, 575mm/μA at 1m.
Secondary galvanometer G_2 : 451 Ω, 3·0sec period, 1 350mm/μA at 1m.
P. Differentially-connected selenium-iron photocells, 22mm × 40mm.

given elsewhere.[11] A light beam reflected from the mirror of the primary galvanometer G_1 falls equally on a pair of selenium-iron photocells P. With the connections shown no current will then flow in the secondary galvanometer G_2. However, if a voltage V_e is applied to the galvanometer G_1, the difference of the thermocouple e.m.f.'s will disturb the photocell balance and galvanometer G_2 gives a deflection x on its scale. If the resistance R is reduced to zero there is no electrical coupling between the two galvanometer circuits. The sensitivity, in terms of the deflection x for a given e.m.f. V_e, is then very high, but the arrangement is also very unstable. Insertion of the resistance R, when the corresponding directions of current flow in the galvanometer circuits are as shown by the arrows, introduces negative feedback from the secondary to the primary circuit. Increasing R reduces the sensitivity but increases the stability of the system. In effect, the suspension of G_1 is stiffened and its period reduced, while the period of G_2 is unaffected.

The light beam for G_1 and P was obtained from a 12-volt 24-watt projector lamp and the precautions recommended by Preston for the optical system were adopted. They include the use of a red-absorbing filter and a sheet of heat-resisting glass to prevent overheating and fatigue of the photocells.

Measurements were made of the sensitivity of the detector for different values of the feedback resistor R, and the results are given in Table 1. The desired sensitivity is therefore obtainable, although the system was becoming increasingly unstable as R was reduced below 100 ohms.

Table 1

DETECTOR SENSITIVITY

Feedback resistance, R	Sensitivity
ohms	mm/μV
5 000	200
2 000	267
900	367
400	567
100	1 770

(2.5) Thermal Aspects

The thermal method of measurement adopted has, in principle, a number of advantages. Since under balanced conditions the rate of rise of temperature in a test is the same in the specimen and the guard strips, no loss of heat from the specimen surface occurs because no temperature gradient normal to the surface exists. Moreover, any thermal disturbance due to flow of heat longitudinally from the test limb to the yokes will similarly affect both specimen and guard strip, and the same is true for any effect due to temperature rise in the magnetizing winding, so that any error from these sources is in any case a difference effect. The temperature rise occurring in individual iron-loss observations is also small; for example, in the extreme case of an iron loss as high as 20 watts/kg, the temperature rise in 4sec is only about 0·2°C. Successive observations could therefore be made without having to allow very long intervals for steady temperatures to be reached as in some thermal methods.

Some preliminary calculations were made to see what effect on the rate of rise of temperature at the centre of the test strip would be caused by longitudinal heat flow from the strip into the yokes. If it is assumed pessimistically that no rise in temperature occurs at the ends of the test limb, the solution to this heat-flow problem given by Carslaw and Jaeger[12] may be applied. It was found with an iron strip that for a 7cm length of the test limb the temperature rise in an interval of 10sec would be approximately 2% lower than for a limb of infinite length. This was considered quite satisfactory, since a similar effect is present in the guard strips and an error of this kind is in any case taken care of by the direct method of calibration already mentioned; this direct method also eliminates possible errors arising from the thermal capacities of the thermocouples and the magnetizing coil.

The magnetizing winding was wound with 0·027in enamel-covered copper wire with 18 layers and 14 turns per centimetre per layer, i.e. a total of 252 turns per centimetre. More copper than this could have been put into this winding at the expense of increasing the leakage impedance. This would have reduced the heating but increased the flux-waveform distortion, and some compromise was necessary. A field strength of 800amp/cm (1 000 oersted), giving an induction in the case of dynamo iron, for example, of 2·21Wb/m², therefore requires a peak current of about 3·2amp. If the current waveform is taken into account the r.m.s. value is about 1·5amp, giving a cal-

* M.K.S. rationalized units.

culated initial rate of rise of temperature of the copper of about 0·08°C/sec. The corresponding rate of rise in an iron specimen with an iron loss as low as, say, 3 watts/kg is about 0·006°C/sec. However, if the thermal capacity and heat insulation of the Bakelite former, and the air spaces in the test limb are taken into account, it is estimated that any error due to heat flow from the winding to the iron during the short 4sec test periods is negligible, particularly since the difference in the rates of rise of temperature of the specimen and the guard strip is the important quantity. Even when H_{max} was raised to the highest value employed, namely 2 000amp/cm, the copper temperature then increasing at the rate of about 0·5°C/sec, the experimental arrangement already described was still considered to be satisfactory. However, it is clear that, to use this method for still higher values of H_{max}, special attention would have to be given at least to the cooling or thermal insulation of the magnetizing winding.

Since the guard strip of 0·010in Nichrome is also inside the magnetizing winding, it will be heated by induced eddy currents produced by the applied magnetic field as well as by the longitudinal current passed through it. When H_{max} is 2 000amp/cm the value of B_{max} in the strip is about 0·25Wb/m². If the resistivity of the strip is 100 microhm-cm, the calculated eddy-current loss is about 0·002 watt/kg, which is negligible when compared with the iron losses. A current of 1amp in the strip gave approximately 2·3 watts/kg; hence the entire range of iron-loss measurements was very conveniently covered by varying the guard-strip current from zero to about 3amp (20 watts/kg).

(3) RESULTS

(3.1) Materials Investigated

Measurements were made on the materials listed in Table 2. Samples 1–6 were ordinary hot-rolled silicon-iron materials as used in motors and transformers. Sample 7 was a grain-oriented transformer iron having, according to a torque test, about 80% of the crystals approximately lined up with a cube-edge in the rolling direction and (110) planes in the plane of the sheet. Sample 8 was a thin sample in the cold-worked condition. This was included as a matter of interest, since the loss is almost entirely due to hysteresis. Also available was a strip of 3% silicon-iron, 3cm wide, which contained several large crystals which spanned the full width of the strip; the test for specimen 8 was on one of these. The cube-edge of the crystal was, however, inclined at 9° ± 2° to the longitudinal axis of the strip. Finally specimen 10 was a cobalt-iron material of the approximate composition given in the Table.

(3.2) Measurements and Corrections: Specimen 1

As a necessary addition to the iron-loss measurements, the relation between M_{max} and H_{max} was determined using the synchronous commutator, and the waveforms of the induction in the specimen and of the applied field were also plotted for a few values of the flux density. The form factors of the e.m.f. induced in the B coil were also determined from cathode-ray oscillograms. This procedure was carried out for every specimen.

Fig. 5 shows the observed relation between M_{max} and H_{max} for specimen 1, and two flux waveforms are plotted in Fig. 6; the flux-waveform distortion occurring at the higher flux density will be noticed. Fig. 7 shows the peaky waveforms of the applied magnetic field as determined from the H coil, while Fig. 8 shows the form factors observed for this specimen the highest of

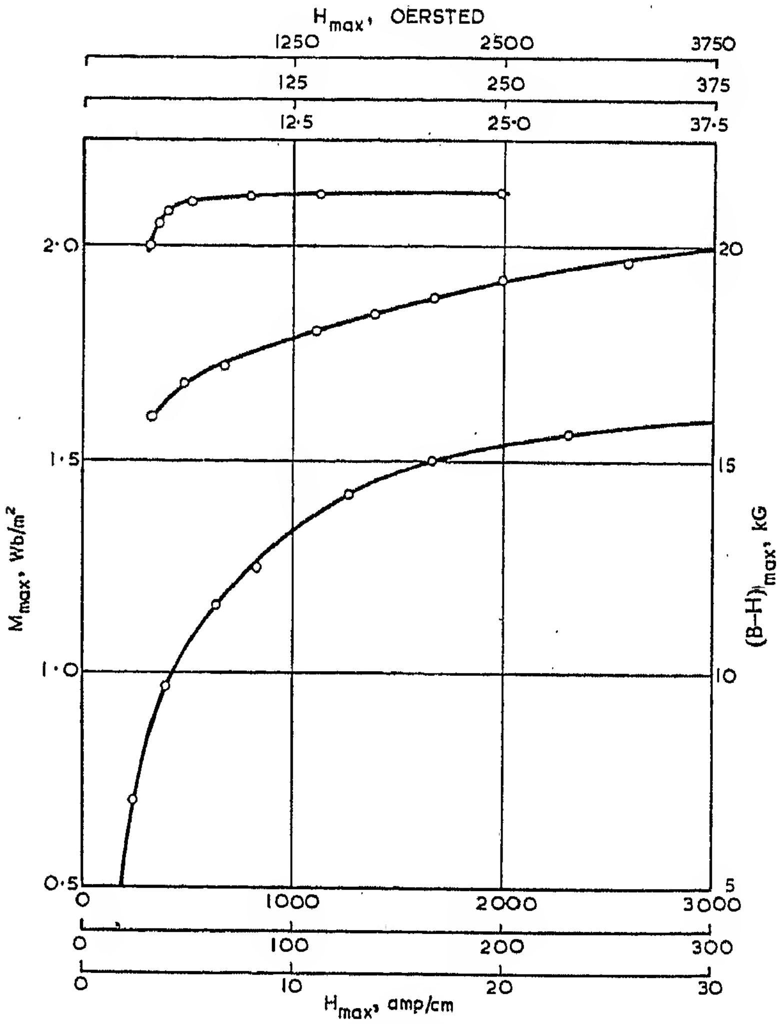

Fig. 5.—Relation between M_{max} and H_{max} for specimen 1.

Table 2

Specimen No.	Material	Direction with respect to rolling	Nominal silicon content	Assumed density	Thickness by weight	Resistivity	Magnetic saturation value M_s
			%	g/cm³	in	microhm-cm	Wb/m²
1	Hot-rolled	Across	0·5	7·83	0·0190	15·0	2·13
2	Hot-rolled	Along	0·3	7·85	0·0159	15·0	2·14
3	Hot-rolled	Along	1·85	7·68	0·0161	36·8	2·06
4	Hot-rolled	Across	4·0	7·55	0·0144	55·0	1·94
5	Hot-rolled	Along	3·5	7·62	0·0077	49·1	1·99
6	Hot-rolled	Across	3·5	7·62	0·0073	48·8	1·94
7	Cold reduced, grain oriented	Along	3·3	7·62	0·0133	50·7	1·98
8	Cold reduced, in cold-worked condition	Along	3·0	7·65	0·0060	47·2	2·00
9	Single crystal	9° from [100]	3·0	7·63	0·0128	47·6	1·98
10	Cobalt–iron: approximately 49% Co, 48% Fe, 2% V + Mn and Si	Along	—	8·15	0·0090	41·2	2·21

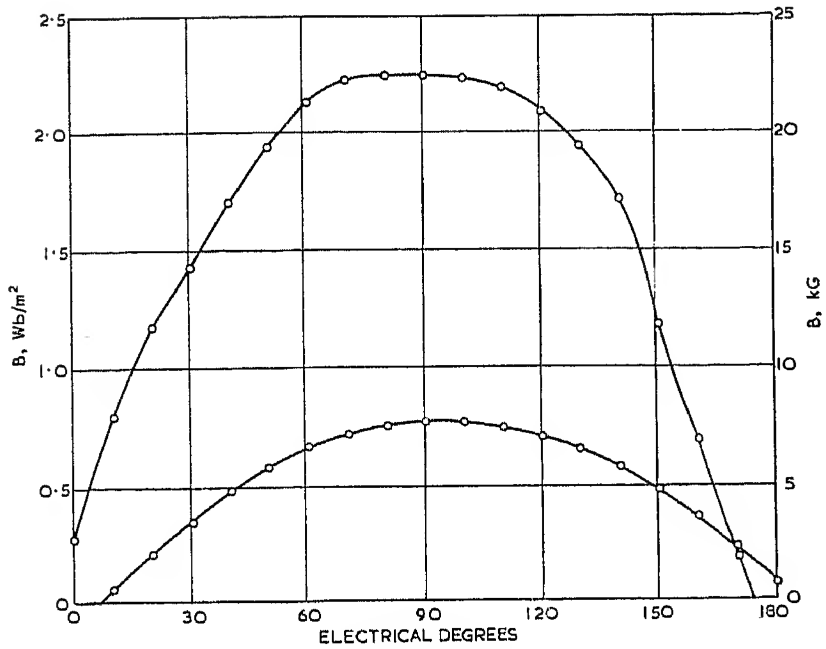

Fig. 6.—Flux waveforms for specimen 1.

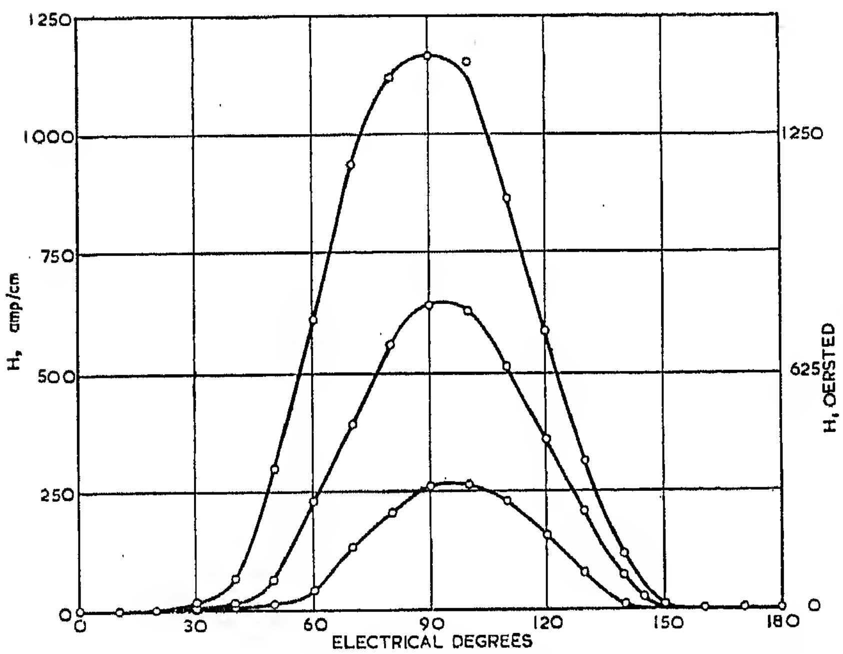

Fig. 7.—Waveforms of applied magnetic field for specimen 1.

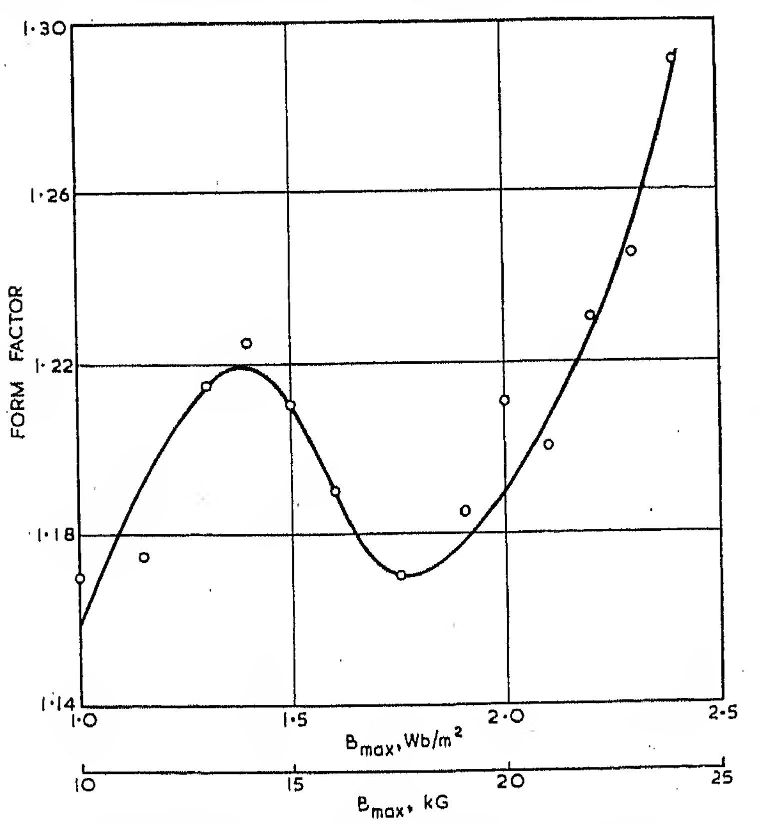

Fig. 8.—Induced e.m.f. waveform factors for specimen 1.

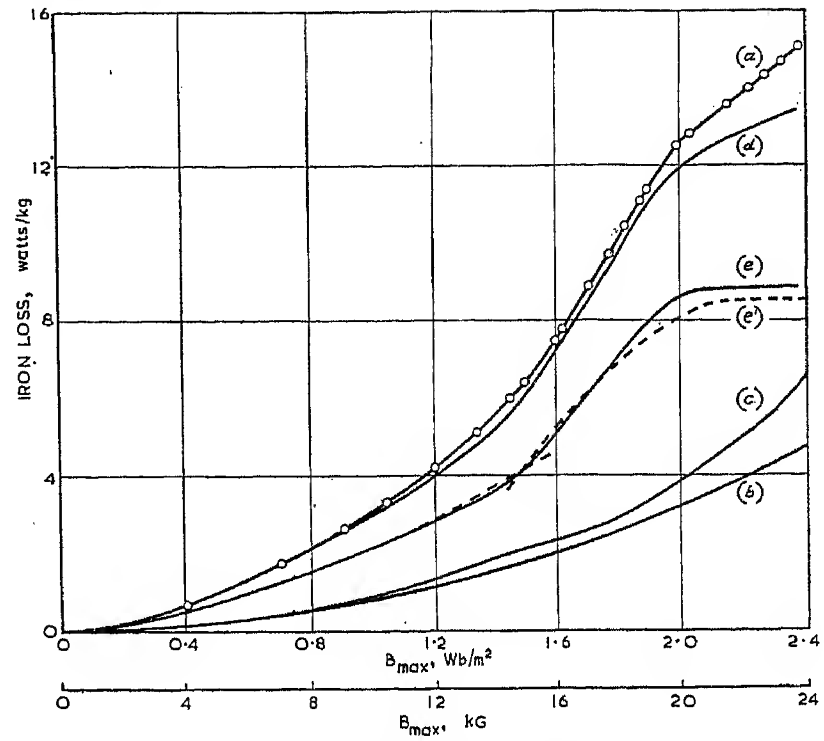

Fig. 9.—Iron losses in specimen 1.

(*a*) Observed total iron loss.
(*b*) Calculated eddy-current loss for sinusoidal flux.
(*c*) Corrected eddy-current loss.
(*d*) Corrected total iron loss.
(*e*) Dynamic hysteresis loss.
(*e′*) Calculated empirical curves.

which is only 1·29. The highest value observed for any specimen was 1·73.

Curve (*a*) in Fig. 9 shows the observed total iron loss for specimen 1. It is desirable to estimate from this what the total loss would have been if a sinusoidal flux had been maintained at all flux densities. It is usually assumed[13] in making this correction that the hysteresis component of the loss is independent of the flux waveform and depends only on B_{max}, while the eddy-current component varies as the square of the form factor of the e.m.f. induced by the flux in the specimen. This method of correction has been adopted. Curve (*b*) is the eddy-current component of the iron loss calculated for sinusoidal flux by the usual formula in terms of the thickness and resistivity of the specimen.[14] To allow for the waveform distortion the values in curve (*b*) must be multiplied by the square of the ratio of the form factors given in Fig. 8 to the form factor of a sine wave. The corrected eddy-current loss is then given in curve (*c*). The difference between curves (*c*) and (*b*) represents the increase in total iron loss due to the distortion of the flux waveform, and when this difference is subtracted from curve (*a*) the resulting curve (*d*) is the total iron loss expected for sinusoidal flux. For this specimen the eddy-current component and the correction are comparatively large, but with some of the other materials, notably specimens 5, 6, 8 and 10, they are relatively small. If now the eddy-current component given by curve (*b*) is subtracted from the total iron loss curve (*d*) [or (*c*) from (*a*)] the result is curve (*e*), which may be called the dynamic hysteresis component of loss, i.e. the hysteresis loss occurring in this case at 50c/s. In this connection it may be noted that it has already been suggested that the calculated and the true eddy-current losses in a thin sheet are unlikely to be appreciably different[15] and that the so-called "anomalous eddy loss" is, in fact, due to a hysteresis effect dependent on frequency[16] and is thus a part of the dynamic hysteresis loss.

The interesting feature about Fig. 9 is that the dynamic hysteresis loss reaches a very definite saturation value. If this saturation persists to still higher inductions, then clearly the total iron loss is also known up to any flux density. A similar result has been found with all the other materials investigated,

although a saturation value is not so positively attained in the cases of specimens 3, 8 and 10.

The overall error in the absolute values of the iron losses measured by this method is considered to be not more than about 5%, with a relative error over any one curve less than this. Other methods of making iron-loss measurements on single strips at lower flux densities have been described, but the necessary equipment was not available to make a direct check with the present method. However for specimen 7 a Lloyd–Fisher test on the whole sample of 32 strips, with a possible error of about 2%, gave iron losses at inductions of both 1·3 and 1·5 Wb/m² which were 7% lower than the corresponding values obtained on the single strip specimen.

(3.3) Results for Specimens 2–10

The results obtained for the other specimens were dealt with in the same way as for specimen 1, the iron-loss curves being given in Figs. 10–12. In each case curve (*d*) is the total iron loss corrected for the waveform distortion and curve (*e*) is the dynamic hysteresis loss. As a general rule the shape of the iron-loss curves reflects the shape of the magnetization curves. A change in slope of the iron-loss curves occurs at a flux density corresponding approximately to the knee of the magnetization curve, and again when the intensity of magnetization approaches saturation.

(4) DISCUSSION OF RESULTS

(4.1) Complete Iron-Loss Curves

It may be concluded from the results that, when the intensity of magnetization M_{max} reaches its saturation value M_s, the dynamic hysteresis loss p_h also reaches a saturation value p_s. It is therefore possible to draw a curve relating p_h and M_{max} for any of the materials which is the complete characteristic. If desired, the relationship between total iron loss and B_{max} may

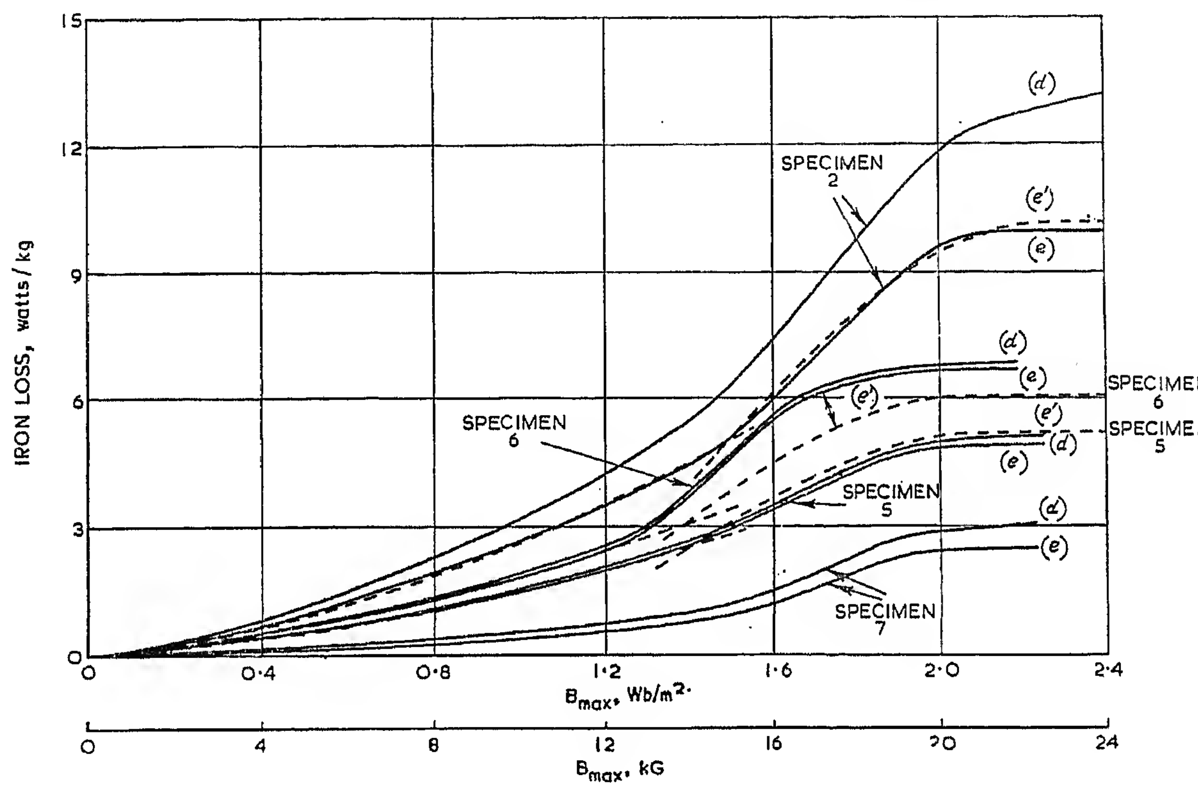

Fig. 10.—Iron losses in specimens 2, 5, 6 and 7.

(*d*) Total iron loss corrected to sinusoidal flux.
(*e*) Dynamic hysteresis loss.
(*e'*) Calculated dynamic hysteresis loss.

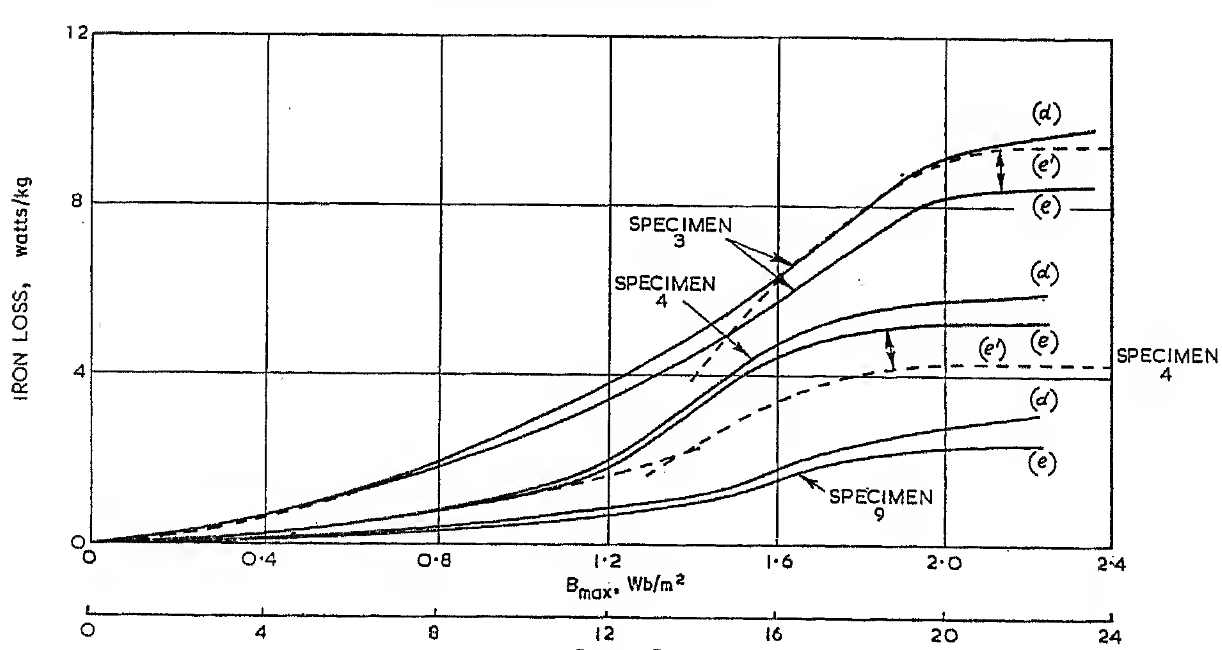

Fig. 11.—Iron losses in specimens 3, 4 and 9.

(*d*) Total iron loss corrected to sinusoidal flux.
(*e*) Dynamic hysteresis loss.
e') Calculated dynamic hysteresis loss.

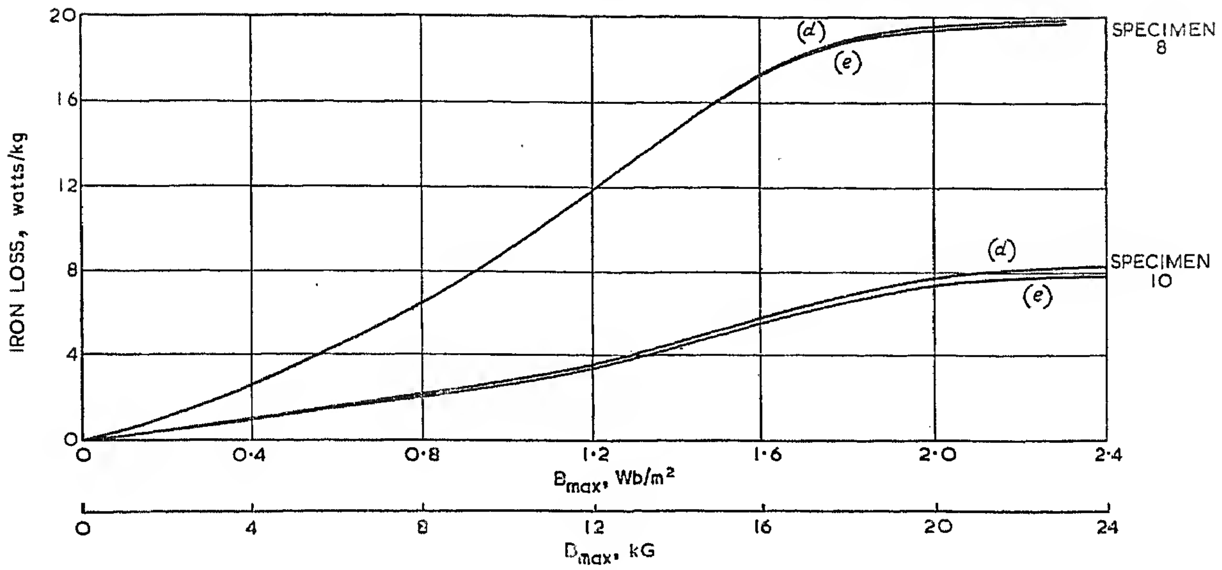

Fig. 12.—Iron losses in specimens 8 and 10.

(*d*) Total iron loss corrected to sinusoidal flux.
(*e*) Dynamic hysteresis loss.

then be plotted up to any value of the induction without apparent limit, provided that the magnetization curve, the thickness and the resistivity of the material are known. The complete relationship between p_h and M_{max} for specimen 1 is shown in Fig. 13. A comparison of the shapes of these characteristics for the hot-rolled fully-annealed materials is given in Fig. 14, in which the ordinates and abscissae are expressed as ratios. Since these particular materials are not specially grain-oriented, a common shape for these characteristics would not be unexpected and is seen to be very approximately realized.

(4.2) Derivation of Empirical Formulae

The practical usefulness of a complete iron-loss characteristic of known shape for a particular type of material would be that iron losses at high flux densities might be estimated from measurements easily made by standard routine methods at lower densities. Empirical equations for this characteristic will now be found.

The knee of the magnetization curve of a single crystal of iron or silicon-iron for a cube-face diagonal direction, [110], occurs theoretically when the value of the magnetization is $1/\sqrt{2}$ of the saturation intensity. For polycrystalline material with a random disposition of the constituent crystals the knee of the curve is also somewhere near this value of the magnetization. There is a rounded discontinuity, not only in the magnetization curve at this point, but also in the hysteresis-loss curve. This has previously been commented on and indeed can also be seen in Fig. 14. It will be assumed that any characteristic drawn to fit the experimental points in Fig. 14 for any of the specimens is made up of curves OP and PS intersecting at P, the co-ordinates of which are

$$m = M_{max}/M_s = 1/\sqrt{2}$$

and

$$p = p_h/p_s = 1/2$$

The Steinmetz equation $p = am^n$ will be assumed for curve OP, where a is a coefficient and n is a suitable exponent.[17] Since the curve passes through P, $a = 1/2^{(1-n/2)}$, and therefore the equation of OP becomes

$$p = \frac{m^n}{2^{(1-n/2)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Analogously, the equation of curve PS will be assumed to be $(1 - p) = b(1 - m)^n$, where b is a coefficient and the same exponent n is arbitrarily retained. Since this curve also passes through P,

$$b = \frac{1}{2^{(1-n/2)}[\sqrt{2} - 1]^n}$$

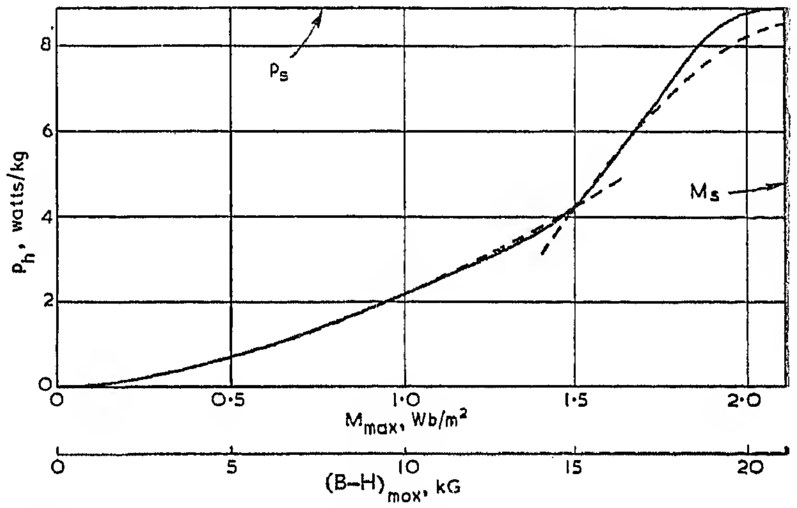

Fig. 13.—Complete hysteresis-loss characteristic—specimen 1.

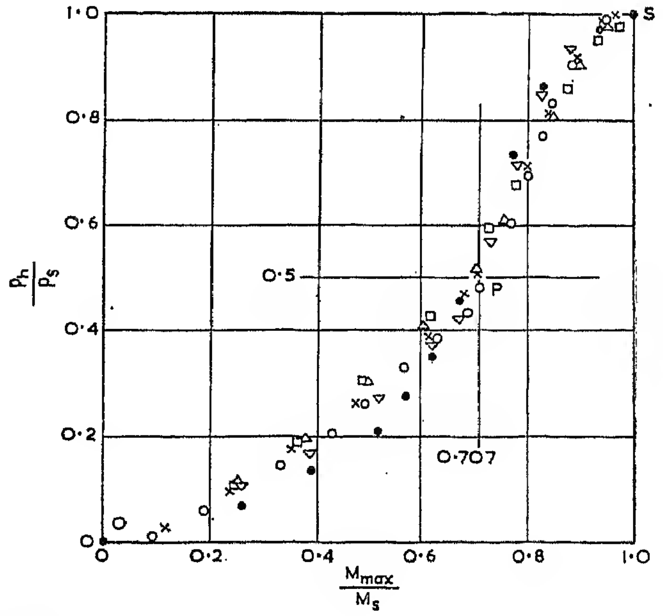

Fig. 14.—Shape of hysteresis-loss characteristics for hot-rolled silicon-iron materials.

⊙ Specimen 1
× Specimen 2
⊡ Specimen 3
● Specimen 4
△ Specimen 5
▽ Specimen 6

and hence the equation of PS becomes

$$1 - p = \frac{(1 - m)^n}{2^{(1-n/2)}[\sqrt{2} - 1]^n} \quad . \quad . \quad . \quad . \quad (2)$$

Eqns. (1) and (2) are general relations in which the variables are in the form of ratios. However, substituting p_h/p_s for p and M_{max}/M_s for m gives for curve OP:

$$p_h = a'M^n_{max} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where

$$a' = \frac{p_s}{M_s^n 2^{(1-n/2)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In M.K.S. units a' is clearly the hysteresis loss in watts per kilogramme when $M_{max} = 1\,\mathrm{Wb/m^2}$ (10 kilogauss). If this loss is known as well as the saturation value M_s and the Steinmetz exponent n for the lower part of the curve, eqn. (4), if the empiricisms are well founded, enables the saturation value of the hysteresis loss, p_s, to be calculated.

Eqn. (2) may also be rewritten as

$$p_h = p_s - b'(M_s - M_{max})^n \quad . \quad . \quad . \quad . \quad (5)$$

where

$$b' = \frac{p_s}{M_s^n 2^{(1-n/2)}(\sqrt{2} - 1)^n} = \frac{a'}{(\sqrt{2} - 1)^n} \quad . \quad . \quad (6)$$

If these empirical relations based on certain arbitrary assumptions can be shown to fit the observed iron-loss curves, the upper parts in any given case become calculable when only the lower parts are known. In fact, the entire characteristic would be known if only a', the hysteresis loss at $1\cdot 0\,\mathrm{Wb/m^2}$ and the exponent n are known. Hence also, if the magnetization curve and the thickness and resistivity of the specimen are known, the complete curve relating the total iron loss with B_{max} may be drawn up to any value of the induction.

(4.3) Application of Empirical Formulae to the Experimental Results

The foregoing theory has been applied to all the specimens to which it is applicable, namely to the hot-rolled silicon-irons specimens 1–6. In general, for points below the knee of the magnetization curve M_{max} is nearly equal to B_{max}. Above the knee, B_{max} is obtained by adding the appropriate value of $\mu_0 H_{max}$ to M_{max}.

For specimen 1 the observed value of p_h at $1\,\mathrm{Wb/m^2}$ was $2\cdot 25$ watts/kg; therefore $a' = 2\cdot 25$. The exponent n on the lower part of the curve was found to be $1\cdot 57$, whence $p_h = 2\cdot 25 M^{1\cdot 57}_{max}$. The broken line shows this curve in Fig. 9 to be in reasonably good agreement with the experimental curve. Then with $a' = 2\cdot 25$, $n = 1\cdot 57$ and $M_s = 2\cdot 13$, eqn. (4) gives $p_s = 8\cdot 59$ watts/kg. This is 3% lower than the observed value of $8\cdot 85$ watts/kg. Then, from eqns. (5) and (6), the equation of the upper part of the curve is given by

$$p_h = 8\cdot 59 - 9\cdot 00(2\cdot 13 - M_{max})^{1\cdot 57}$$

This relation, using the appropriate values of B_{max}, is plotted in Fig. 9 as the upper broken line (e'). The agreement between the empirical and observed curves would in this case be probably quite good enough for most practical purposes.

Specimen 2 is a material similar to specimen 1, although in fact obtained from a different supplier. The experimental value of p_h at $1\cdot 0\,\mathrm{Wb/m^2}$ was $2\cdot 65$ watts/kg. This value for a' and the assumption that n would be $1\cdot 57$ as for specimen 1 gives the following equations:

$$p_h = 2\cdot 65 M^{1\cdot 57}_{max}$$
$$p_h = 10\cdot 16 - 10\cdot 6\,(2\cdot 14 - M_{max})^{1\cdot 57}$$

The broken line e' shows these curves in close coincidence with the observed result for specimen 2 in Fig. 10. Such remarkable agreement is perhaps fortuitous. In this case the predicted value of p_s is $10\cdot 16\,\mathrm{Wb/m^2}$, which is about 3% greater than the observed value of $9\cdot 90$ watts/kg.

For specimen 3, the values found for a' and n were $2\cdot 63$ watts/kg and $1\cdot 56$, with $M_s = 2\cdot 06\,\mathrm{Wb/m^2}$. The equation of the upper curve is then

$$p_h = 9\cdot 42 - 10\cdot 42(2\cdot 06 - M_{max})^{1\cdot 56}$$

The empirical curves are given by the broken lines in Fig. 11 and are to be compared with curve (e) for specimen 3. The agreement is now not so good, the predicted value of p_s being 11% higher than the observed value.

The equations obtained for the remaining materials are plotted in Figs. 10 and 11. They are as follows:

Specimen 4: $p_h = 1\cdot 20\, M^{1\cdot 83}_{max}$
$p_h = 4\cdot 28 - 6\cdot 02(1\cdot 94 - M_{max})^{1\cdot 83}$

Specimen 5: $p_h = 1\cdot 51\, M^{1\cdot 57}_{max}$
$p_h = 5\cdot 17 - 6\cdot 04(1\cdot 99 - M_{max})^{1\cdot 57}$

Specimen 6: $p_h = 1\cdot 83\, M^{1\cdot 57}_{max}$
$p_h = 6\cdot 00 - 7\cdot 32(1\cdot 94 - M_{max})^{1\cdot 57}$

The empirical results for specimens 4 and 6 are not very satisfactory, but agreement is again quite good for specimen 5.

(5) CONCLUSION

A method of measuring iron losses in sheet materials at any flux density, including flux densities in the magnetic saturation region, has been described. The results obtained at 50 c/s indicate that the hysteresis component of the total loss for iron, silicon–iron and cobalt–iron reaches a saturation value at high flux densities.

An empirical relation between hysteresis loss and intensity of magnetization is proposed for the upper part of the loss curve and for use with hot-rolled non-oriented silicon–iron materials. This is in such a form that the upper part of the loss curve may be predetermined if the lower part is known. The relation is found to apply closely to two samples of dynamo iron, moderately closely to a sample of 3·5% silicon–iron, but only indifferently to three other silicon–iron materials.

(6) ACKNOWLEDGEMENTS

The authors are indebted to Messrs. Richard Thomas and Baldwins, Messrs. Sankeys, the Steel Company of Wales (Newport), and the Telegraph Construction and Maintenance Company for the supply of specimens and other materials. They also wish to thank the Electrical Research Association for financial help in the purchase of some of the measuring equipment, and the Metropolitan-Vickers Company for orientation tests on specimen 9. One of them (C. G. B.) was also aided by a maintenance grant from the Department of Scientific and Industrial Research. The work was carried out in the Electrical Engineering Department of University College, London.

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DISCUSSION ON THE ABOVE PAPER AND A PAPER BY C. D. MEE AND R. STREET,* BEFORE THE MEASUREMENTS SECTION, 1ST MARCH, 1955

Dr. L. G. A. Sims: The experiment described in the paper by Prof. Brailsford and Dr. Bradshaw is very ingenious and seems a most excellent piece of work. Certain points in the paper are non-contentious. For example, in Section 2.1 the authors refer to the specific heats of the types of magnetic laminations with which they were concerned, and I think it is agreed that information is not available about the specific heat or the heat capacity of packs of these laminations. Cases occur in which that quantity can be really important. It has been stated elsewhere that modern steel laminations are manufactured with no oxide scale on them, and I would be interested to know whether this is generally true.

In Section 2.3 I was momentarily nonplussed by the expression given for H_{max} as 2 kA/cm. However, it is merely a statement of the magnetizing force expressed in the M.K.S. system. It is another instance where the rationalized M.K.S. system, which is enjoined upon all of us, produces some very unexpected and unfamiliar results. Magnetizing force is expressed in amperes and not in ampere-turns. It used to be particularly stressed that magnetic effects depended on ampere-turns. That was the whole burden in the earlier days of magnetic design. I am well aware of the arguments which are advanced in favour of the new system. Engineers have now to remember two constants which were not needed before. One is $4\pi \times 10^{-7}$ and the other is $8 \cdot 855 \times 10^{-12}$.

It is suggested that the heat loss is very small because the heating time is small. I know the authors do not really mean that the heat loss is entirely negligible, but there is a certain correlation of the idea that, because the heating time is small, the heat loss is small. If the temperature rises at the surface, however short the time, then heat loss continues just the same. It is a fallacy to think that because one cuts down the heating time, one can cut out the heat loss. The two must remain linked together, and the shortness of time cannot be used as an argument in favour of neglecting the heat loss—at any rate in an experiment in which surface temperature is used.

In Section 2.3 it is stated that the mean area of the B coil *cannot* be determined exactly. If the B coil is calibrated in a standard field, as I presume the H coil was calibrated, and the number of turns is known, the mean area should be immediately available.

What degree of accurate overlap was achieved with the results obtained from other longer-established methods, not only in one case but in all cases?

I am very much impressed by the great difficulty involved in making accurate thermal measurements. The authors' arguments are closely reasoned, and they suggest that inaccuracies in making measurements on a single strip like this have all been taken into account. But I still wonder whether that is really the case.

Under the methods used by the old classical experimenters, every factor and piece of apparatus in the experiments was changed to make quite certain that nothing was weighting the results. This was standard procedure, and the results had to withstand that stringent test. Would the authors guarantee that their apparatus could be expected to repeat the results with accuracy? What degree of accuracy would have been attained if, for instance, the simple test had been applied of dismantling and reassembling the apparatus and repeating the measurements?

Mr. R. G. Martindale: The paper by Prof. Brailsford and Dr. Bradshaw is a very valuable contribution to the subject of iron-loss measurement. It is the first time that iron losses have been measured at flux densities as high as 23 000 or 24 000 gauss, and the information given in the paper will be valuable to the machine designer, who has not hitherto known the order of the losses to be expected at these flux densities. It is interesting to see the way in which curves (*e*), which are called the dynamic hysteresis loss, in each case turn over and approach a saturation value, particularly as they also include the so-called anomalous loss.

In the paper by Dr. Mee and Dr. Street, the arrangement of two Permalloy rods wound in series opposition, so that the fundamental component in the secondary winding is practically eliminated, is a good one. Would the authors give some idea of the volume over which the flux-gate detector measures the field? How far apart are the Permalloy rods and how long are they?

* "An Improved Precision Permeameter," Paper No. 1746 M, December, 1954 (see **101**, Part II, p. 639).

I was most interested in the comparative B/H curves obtained by different methods and given in Figs. 4 and 6. Whilst Fig. 6 shows good agreement between the three methods for a material having a maximum permeability of 12000, the agreement shown in Fig. 4 for grain-oriented sheet, having a maximum permeability of 50000, is rather poor. It is difficult to see why this should be so. No evidence has been reported previously that, if the field at a fixed point inside the magnetizing coil of the permeameter is adjusted by compensation to be the same as without the specimen present, there may be a radial variation in H, as suggested in the paper. This method of adjustment for uniform H is used in obtaining the curves denoted "ballistic measurement." A radial variation in H of the order of 30% at an induction of 12 kilogauss, as implied by Fig. 4, could easily be detected by turning the flux gate so that the plane through the two Permalloy rods was perpendicular to the plane of the specimen, in which case the double-frequency signal could never be completely eliminated. Did the authors make such a check for radial non-uniformity of H?

What was the grain size of the oriented material? If the flux-gate detector is not large compared with the grain size, variations in the measured value of H would be expected as the detector is moved over the surface of the specimen. Furthermore, magnetic inhomogeneity arising from comparatively large grain size might lead to error in deducing the average value of H for the material from measurements made close to the surface of the specimen. It seems that the validity of measuring B/H curves for high-permeability large-grain grain-oriented material, by the methods described, might be in question unless steps were taken to ensure that the average properties were obtained, as would apply in tests on annealed spiral cores or in long solenoids.

Prof. J. T. MacGregor-Morris: Fig. 9 of the paper by Prof. Brailsford and Dr. Bradshaw is of singular value. It is very difficult to find out what is happening as we approach alternating saturation in iron. Often there is thermal trouble, e.g. heating of the magnetizing coil, which prevents results of any value being obtained.

In his early books, Steinmetz gives a curve of the a.c. losses in iron at various flux densities, and, as saturation is approached, the points on the curves become irregular, but there is a tendency for the curve to incline over. However, we are now on a firm foundation.

We know that the losses in sheet steel vary considerably over a single sheet. I should like to see tests on a number of specimens which have been cut from the same sheet but from different places and at right angles to one another. I know it entails more work, but I should like to know whether the turn-over point comes at the same place for each of the specimens cut from one sheet, and at the same time I should like to know the range of losses for the various samples at a given induction density.

The losses in a sheet can be measured in one of three ways:

(i) At a point as in Reference 7.
(ii) For the sheet as a whole as by Dannatt, Astbury or Emmerson.
(iii) By the method described in the paper, where a small strip measuring 7 cm × 3 cm is used.

In addition there are the Epstein and Lloyd–Fisher square assemblies, where the whole sheet is cut up into a number of strips and an average figure for the loss in the sheet as a whole obtained.

The electrical designer wants to know which of the above tests should be specified in order that the figure supplied him for the loss is sufficiently reliable for his purpose, whilst at the same time being as economical as possible in time and money.

Apparently the tests were made at or very near room temperature. How would the curves be altered if the temperature were raised by, say, 20° C?

Mr. C. E. Webb: In the paper by Prof. Brailsford and Dr. Bradshaw, can the authors explain the shape of the curve shown in Fig. 8? Prof. Astbury* showed that distortion is directly related to the electrical circuit constants and the shape of the hysteresis loop. It would therefore be expected to increase progressively with B_{max} above the point of maximum permeability (unless changes in the electrical circuit were made), and this normally occurs.

I wish to deal mainly with the application of the authors' work to commercial testing. Have they considered the possibilities of adapting their method or developing a method on similar lines which would be suitable under such conditions? The prospects do not seem promising, and the alternative of deriving a general expression which would allow the losses at saturation to be deduced from measurements in the normal working range, is therefore worth exploring. Fig. 14 suggests the possibility of such an expression for hot-rolled materials, but I do not think the authors have made the best case for a determination of the losses at saturation by extrapolation. They have been a little seduced by the mathematical neatness of their solution based on Steinmetz's constant-exponent law. It is well known that, as occurs in specimens 4 and 6, the hysteresis loss often increases, between $B_{max} = 10$ kG and about 15 kG, much more rapidly than would be expected on the basis of the constant exponent normally observed below 10 kG. Let us therefore confine the extrapolation to the region above $B_{max} = 15$ kG. The saturation loss p_s can be computed from the loss, p_h, at some convenient magnetization M_{max}, using eqns. (5) and (6) which yield

$$p_s = p_h + a' \left[\frac{M_s - M_{max}}{\sqrt{(2)} - 1}\right]^n$$

where a' = Loss at 10 kG.

Results calculated in this way, taking $M_{max} = 15$ kG, are compared with the measured values of p_s in columns 2–4 of Table A.

TABLE A

Specimen number	Values of p_s: Measured	Values of p_s: Calculated from p_h at 15 kG	Discrepancy	Values of p_s calculated from p_h at 16 kG	Discrepancy
			%		%
1	8·85	8·6	−3	8·4	−5
2	9·9	10·3	+4	10·05	+1·5
3	8·5	9·25	+9	8·95	+5
4	5·3	5·15	−3	5·25	−1
5	4·95	5·05	+2	4·75	−4
6	6·65	6·55	−2	6·85	+3

The agreement is very good except for specimen 3. Better results may be expected if a higher value of M_{max} is used, and columns 5 and 6 show that, taking $M_{max} = 16$ kG, no discrepancy exceeds 5%, which is the order of accuracy of the measurements. It may well be that some better empirical basis for extrapolation could be found, and further results on each of the main grades of sheet steel are needed to establish the most reliable method, but the above examination suggests that the loss at saturation can be deduced, with all the accuracy that is of practical significance, from loss measurements at the standard flux densities of 10 and 15 kG, with possibly one lower flux density, say 5 kG, to enable the exponent n to be determined.

* ASTBURY, N. F.: "Some Aspects of the Theory of Iron-Testing by Wattmeter and Bridge Methods," *Journal I.E.E.*, 1948, 95, Part II, p. 607.

Confirmation of this view by further investigation is desirable, and no effort should be spared to ensure that the results of this valuable piece of research are applied to the best advantage.

Mr. O. I. Butler: The results contained in the paper by Prof. Brailsford and Dr. Bradshaw suffer from the serious disadvantage that they do not correspond to simple standard waveforms of alternating total flux or surface magnetizing force. One of these standard and repeatable conditions must be complied with, particularly for high values of magnetization, if the results are to be of real general and scientific value and capable of being theoretically extrapolated with confidence to still higher values of magnetization.

For example, the authors assume that the eddy-current loss varies as the square of the form factor of the e.m.f. induced by the total flux in the specimen. This is true for the eddy-current loss occurring at the surface of a lamination. However, the waveform of the eddy-current e.m.f. changes with the displacement from the surface towards the centre of the lamination, and therefore it is unlikely that the correction factor applicable to the surface is applicable also throughout the lamination thickness. Thus an unknown error is incurred by the authors in the calculated value of the eddy-current loss for sinusoidal total flux conditions.

Furthermore, it is known that the magnetizing-circuit parameters can influence the apparent loss of a specimen when harmonics of both current and e.m.f. are present. Thus, in order to avoid the difficulties of reproducing identical circuit parameters in the different laboratories of manufacturers and users in an attempt to obtain a basis for comparison of the measured loss, it is necessary to specify that no harmonics of surface magnetizing force of the specimen are present, or, alternatively, that no harmonics of total flux in the specimen are present. Neither of these conditions can be obtained in a really simple manner at high magnetizations, although I am at present using a fairly simple form of feedback circuit to produce a sinusoidal surface-magnetization condition corresponding to a mean flux density appreciably greater than that attained by the authors; and a multi-frequency motor-generator set, giving variable phase and amplitude of the harmonic currents to produce a close approximation to sinusoidal total flux in the specimen. The latter is similar to the method used by Cormack,* although certain modifications have been made to obtain higher magnetizations and to overcome the difficulties of power measurement.

The authors state that "preliminary measurements confirmed that there was a negligible variation of flux density along the test length of the specimen." This point might well have been taken for granted, since it has been substantiated by Hammond.† However, it cannot be taken for granted that the H coils used by the authors give a true record of the magnetizing force at the surface of the specimen. In Fig. 3 it is unlikely that the H-coil D embraces a uniform horizontal flux for the whole of its length and depth for every value of H in a magnetizing cycle. I have found it necessary, with my equipment, to limit the length of the H coil to less than half the available length between the ends of the yoke. It is possible that Fig. 3 is misleading on this point.

Would the authors confirm that transient-current effects in closing the switch S in Fig. 1 failed to produce a degree of polarization of the core, or initial rate of heating of the strip C, which appreciably influenced the initial relative rates of rise of the temperatures of the specimen and the strip C? The authors' method of measurement is based essentially on the initial relative rates of rise of temperature, and therefore transient effects could lead to appreciable inaccuracy of the measured loss. Furthermore, if polarization is involved, the measured loss by such a method corresponds to waveform conditions different from the steady-state waveforms recorded in the paper.

Could the authors state the upper limit of magnetization conditions at present encountered in the various applications of magnetic materials at power, and higher, frequencies? I suspect that, at some points in certain machines and equipment, the upper limit is appreciably beyond that of the test results given in the paper. In any case, it seems that only by obtaining a more certain knowledge of the losses involved at extremely high magnetizations will it be possible to ensure that "hot spots" are avoided, in making the maximum use of magnetic materials in present and future machines.

Mr. E. Rawlinson: With regard to the paper by Dr. Mee and Dr. Street, one of the great troubles and time-wasters in the use of a permeameter is the establishment of uniform flux. It seems, therefore, that to have a direct indication of the lack of compensation is admirable in general and almost essential for the measurement of hysteresis loops on high-permeability materials. In the normal method of obtaining a hysteresis loop we work down from the saturation point, or from the peak value of H with which we are concerned, to zero to get the remanence, and to compensate correctly we are trying to notice a small change in a large measured value. With high-permeability materials a slight change in H near zero will produce a very large change in B. The direct indication of the lack of compensation overcomes that problem.

The authors quote Reference 3 for the statement that the disturbance of the magnetizing field due to the proximity of the detector is only 1%. The formula involved is that the fraction of the field which might exist in the sample near the detector, owing to the detector being there, is $\frac{1}{2}(d_c/l_c)^2$, where d_c is the diameter of the coil inside which there is no flux and l_c is the length of that coil. For 1% accuracy, it would appear that l_c should be greater than $7d_c$. From the figures given by the authors, in this case it was only $5d_c$.

With reference to the use of the detector for the measurement of H it seems that one of the factors involved is the demagnetizing factor of the Permalloy rods. The ratio of the length to the diameter is about 60 : 1, which gives a demagnetization factor of 10^{-3}, and the permeability of the Permalloy will be about 100 000. The apparent permeability will therefore be about ten times less than the true permeability. Is it possible, by using thinner or longer Permalloy wire, to obtain still higher sensitivities in that direction?

What is the amount of feedback? In other words, what change of H is necessary to produce the feedback current? For instance, if it was, say, 100 : 1 and we were using one of these instruments to measure a value of H of 1·2 oersteds, a field of 0·01 oersted would still exist on the Permalloy rods; that would in itself produce quite a high flux density. It would perhaps be about 1 000 gauss in the Permalloy rod itself. Could this lead to an error?

In using a flux gate as an H-measuring device, if it were placed in a field of 3 or 4 oersteds it seems that everything would be saturated and the detector in the feedback circuit would return to zero. Is there any way of knowing whether this has happened?

Have the authors considered using one of these devices to measure a low-frequency a.c. field? One would obviously get a modulated signal from the search coil of the flux gate.

Prof. H. E. M. Barlow (*communicated*): In interpreting the experimental observations recorded in Figs. 9, 10 amd 11 of the paper by Prof. Brailsford and Dr. Bradshaw, the eddy-current component of the total iron loss making a correction for the

* CORMACK, W.: "The Development of a Magnetic Testing Apparatus to Determine Iron Loss at High Flux Densities," *Transactions of the South African Institute of Electrical Engineers*, 1947, 38, p. 257.

† HAMMOND, P.: "Leakage Flux and Surface Polarity in Iron Ring Stampings," *Proceedings I.E.E.*, Monograph No. 116, January, 1955 (102 C, p. 138).

form factor of the flux wave is calculated. The authors then proceed to deduce curve (*e*), which is represented as the hysteresis loss. This curve becomes horizontal at high flux densities and thus indicates a hysteresis component of the total loss depending only on B_{max}. It certainly seems likely that this interpretation is the correct one, but I think that attention should be drawn to the fact that any inaccuracy in the calculation of the eddy-current loss will introduce a corresponding inaccuracy in the hysteresis loss. What evidence exists for the assumption that at these very high flux densities, when the waveform is seriously distorted, the same correction for form factor can be applied in calculating the appropriate eddy-current loss as at low flux densities?

I would also suggest that the problem of obtaining the very high flux densities required in the specimen, without overheating, might possibly be tackled by using a permanent magnet supplemented by a magnetizing coil. The permanent magnet, or perhaps alternatively the specimen, could be rotated in synchronism with the a.c. magnetizing current, so that the two magnetizing forces thus obtained act in support of one another.

Dr. A. J. King (*communicated*): When Prof. Brailsford left industry I was given the responsibility for carrying on his magnetic work, and it is interesting to note that without any collaboration we chose similar ways of tackling the problem. I decided to use a single 4 in-wide test strip in a magnetizing yoke and to determine by means of a thermocouple and galvanometer the initial rate of rise of temperature of the strip under a.c. magnetization, followed by the reproduction of that initial rate of rise by passing direct current through the strip. As in the the authors' case, the short heating time, which was sufficient to determine the initial rate of rise of temperature, minimized losses. My choice of a single strip for both a.c. magnetic heating and d.c. resistance heating gave a direct calibration independent of the specific heat of the test strip and so avoided one of the authors' uncertainties, although they carried out a check in the same way. However, this choice lost the authors the advantage of a null method, since the photo-electric amplifier has to remain constant in sensitivity between the a.c. and d.c. runs although the absolute temperature sensitivity is unimportant. A large magnetizing coil and yoke were used to try to obtain a trapezoidal flux wave similar to that obtaining in armature teeth. However, when the results were analysed, as in the paper, by substracting the calculated eddy-current loss from the total loss, a saturating hysteresis-loss curve similar to that of Fig. 9(*e*) was obtained, and it was realized that with this information it was possible to calculate the total loss for any desired field form. Attempts to produce a particular waveform corresponding to a practical field form were therefore discontinued.

The paper by Dr. Mee and Dr. Street describes a rapid method of making accurate *B*/*H* and hysteresis measurements using the type of permeameter which my colleagues and I described. The all-important question is whether the presence of the flux gate with its magnetic vacuum near the specimen nullifies to an appreciable extent the criteria for field uniformity which we laid down. Since radial uniformity of field and a magnetic vacuum are clearly incompatible, it is a matter of degree which must be settled for the whole range of permeabilities to be encountered in testing. It would obviously be preferable to have a continuous indicator of flux, such as a small rotating coil connected to a measuring instrument, which did not disturb the field it set out to measure. We have toyed with the design of such a flux-measuring device, but there are several difficulties. An alternative course might be to use a small piece of Silmanal to indicate by means of a pointer or reflected light beam when the magnetizing field is accurately parallel to the coil axis and specimen surface. The low permeability of Silmanal, together with the use of a very small piece, would ensure negligible distortion of the field. However, the authors have satisfied themselves that the effect of the flux gate is negligible, and I assume this applied to the highest-permeability materials tested. In this connection the greatest divergencies in Fig. 4 are at the highest permeabilities, as would be expected.

Mr. D. Edmundson (*communicated*): The paper by Prof. Brailsford and Dr. Bradshaw provides a complete solution to one of the few outstanding practical problems in power-frequency magnetic measurements. All who have to employ these materials at high flux densities, particularly in a.c. machines, will remain in the authors' debt. From the practical standpoint one can only hope that the work may be extended, for it is notorious that results on a single specimen of any nominal grade of sheet may be far from typical of the average.

Besides the results of practical utility we must always look, in pioneer work in a new field, for conclusions which may throw some light on fundamental problems. The authors find some indication that a quantity which they describe as the "dynamic hysteresis loss" becomes constant. This loss is not the value usually found by "separation," or that which would be obtained by measuring the area of a static loop; it is simply the total loss minus the eddy-current loss calculated on the assumption of low permeability. One of the few real criticisms which can be offered is that errors in the use of this quantity in the correction of loss for form factor are not assessed. They would undoubtedly be substantial at flux densities over the range 10 000–15 000 gauss. By definition, the quantity is frequency-sensitive. The authors' measurements were made at 50 c/s. Is it merely a coincidence that the "dynamic hysteresis" approaches constancy at this frequency? Would it continue to rise at 100 c/s or even fall at lower frequencies? Or are the differences too small to be taken into account?

Such questions can only be answered by more extended work at other frequencies. The measurement problem has now been solved, but there is ample scope for further work on the intrinsic problems of magnetic materials at these high flux densities.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSION

Prof. F. Brailsford and **Dr. C. G. Bradshaw** (*in reply*): We agree with Dr. Sims that it cannot be argued that, because the heating time is small, the heat losses from the surfaces of the strip specimen are also small. The important points in this case are that there is no difference in temperature between the specimen and the neighbouring guard strips and that there is negligible error at the centre of the specimen owing to heat flow by conduction to the yokes. Dr. Sims, however, probably has in mind the possibility of thermal interference owing to the different rates of rise of temperature in the magnetizing coil and the test limb. This again involves a difference between such effects on the specimen and guard strip, respectively, and within the range of flux densities covered in our measurements we considered that this introduced no appreciable error. However, special attention to the design and heat insulation of the magnetizing winding would be required if this method were used to extend the measurements to much higher flux densities.

The difficulty in determining the mean area of the *B* coil is due to the fact that, in order to keep the air flux small, it is wound directly on to a very thin specimen from which it is not detachable for calibration purposes.

Very great effort is required, as Dr. Sims states, to obtain a high degree of absolute accuracy in measurements, but whether that effort is justified or not depends on the nature and object

of the investigation. We have aimed, with these variable magnetic specimens, at good relative accuracy in order to enable the shapes of the iron loss curves to be determined and do not claim better than 5% for the absolute accuracy.

Measurements have been made at room temperature only, and much more elaborate equipment would be required to repeat the tests at higher temperatures as Prof. MacGregor-Morris would like. It is unlikely that the iron losses would be altered by more than about 1% by a rise of temperature of only 20° C.

In reply to Mr. Webb the dip in the form-factor curve shown in Fig. 8 is due to changes in the phase positions of the harmonics in the e.m.f. wave. For example, if a third-harmonic component is moved in phase position relative to the fundamental, the average value of the total wave varies while the r.m.s. value is unchanged. We are pleased to see from Mr. Webb's calculations that the loss at saturation may be calculated with no discrepancy greater than 5% if values of the observed loss at 10 and 16kG are employed in our empirical formula.

Prof. Barlow, and Messrs. Butler and Edmundson have all pointed out that the method of calculating the eddy-current loss is not exact and that any error here will also give an error in the deduced hysteresis-loss component. We adopted the only convenient method and were aware that it introduced some uncertainty. However, it will be noted that in a number of the materials tested the eddy-current loss, even allowing a very great error in its calculation, was a comparatively small part of the total loss. This is the case, in particular, for Specimens 5, 6, 8 and 10, the results for which are shown in Figs. 10 and 12. The dynamic hysteresis loss cannot be greatly in error from this cause in these cases at least.

We are satisfied from repeated tests in the early stages of the investigation that initial transient effects in the specimen on closing the switch, referred to by Mr. Butler, caused no difficulty —a result which indeed was expected since the switch was closed on each occasion for a period corresponding to about 200 cycles.

Drs. C. D. Mee and **R. Street** (*in reply*): The Permalloy rods used in the flux-gate detector are 3cm long and 0·05cm in diameter. They are mounted side by side, 3mm apart, and are enclosed by the secondary and feedback windings. The secondary is the inner of the two windings, and it is through this coil that the backing-off current is fed. The length/diameter ratio of the secondary coil is 8. The overall dimensions of the flux-gate detector are 4cm × 0·8cm. Using Carr's formula for the magnetic disturbance owing to the proximity of the detector to the specimen, the calculated field-measurement error is less than 1%.

The results given in Fig. 4 are typical of the agreement obtained between flux-gate and ballistic measurements for samples of grain-oriented silicon-iron. Compared with the different values of H obtained by the two methods, only minor variations were observed when the flux-gate detector was moved in a direction parallel to the specimen and perpendicular to the flux therein. This suggests that grain-size effects are too small to explain the differences of Fig. 4. In addition, turning the specimens round had a similar small effect on measured values of H. As suggested by Mr. Martindale, some method of measuring the radial variation of H, when a high-permeability strip is magnetized to the knee of the curve, is desirable. The confined space between the specimen and the magnetizing coil did not permit this with the detector described, but it is possible that a single-core detector of small dimensions could be used to make such measurements.

As described in the paper, the sensitivity of the flux-gate apparatus is higher than was required for measurements of H on silicon-iron specimens. However, even higher sensitivities would be expected from cores having a smaller demagnetizing factor and a more rectangular B/H loop. Alteration of the frequency and amplitude of the exciting signal will also influence the ultimate sensitivity of the detector. Using the feedback techniques described, a linearity of one part in 150 is readily obtainable between the feedback current and the external field acting on the detector. If the apparatus is to be used in circumstances where 3–4 oersteds are applied to the detector it will be necessary to increase the current-handling capacity of the d.c. amplifier following the phase-sensitive rectifier.

Flux-gate detectors may be used to measure alternating magnetic fields provided that their frequency is low compared with the exciting frequency. One of the authors (C.D.M.) is at present using a modified form of the detector described in the paper to investigate the alternating fields obtained when replaying signals recorded on magnetic tape. For this application an exciting frequency of 50kc/s is being used, and alternating fields of several kilocycles per second may be measured.

DISCUSSION ON

"THE DESIGN OF HIGH-SPEED SALIENT-POLE A.C. GENERATORS FOR WATER POWER PLANTS"*

NORTH-WESTERN CENTRE, AT MANCHESTER, 6TH MAY, 1952

Mr. J. Douglas: As such large machines are usually supplied with one conductor per coil winding, the difference between the x_d'' and x_q'' is not so important, as there cannot be high inter-turn voltages on a coil if there is only one turn per coil. The resistances of x_d' and x_d'' are very reasonable for solid-shoe machines.

On the question of bearings, the use of water-cooled bushes is a step in the right direction as it does away with pumps and other ancillary apparatus which can be troublesome at times. However, I favour the use of flood lubrication with cooling coils in the pedestals, as this ensures that the bearing always has a large supply of oil. This can be given by the use of discs on the shaft.

Dr. R. W. Bailey: When the authors gave their previous paper I made the comment that, judged by bursting speed, too much respect had been paid to elastic theory in believing that the presence of a bore reduced the bursting speed to the extent indicated by the theory. If in the designs of rotor bodies shown by Fig. 4 a similar regard for elastic theory had been maintained, one would suggest that full advantage has not been taken of the material, particularly if the information given in the paper, in connection with the T-head fastenings, as to runaway speeds and factors of safety, would also apply to rotor bodies; i.e. a factor of safety of 1·5 on the yield point at a runaway speed of 1·8 to 2·2 times normal speed. Or, the normal speed stress would have a factor of safety referred to the yield point of 4·86–7·26 and referred to the ultimate strength assuming that the yield point is 60% of the ultimate tensile strength of 8·1–12·1. These working stresses would clearly be very low and the factors of safety very high, as commonly considered. They call for a critical attitude on the subject of essential factors of safety if proportions are not to be excessive for the needs of assured safety.

The difficulty arises, of course, from the runaway speed margin demanded, and as perhaps no relief is to be expected from this quarter, attention must be concentrated upon what are the real properties of the material used and how they are related to yielding, repeated application of peak stresses, and failure.

A sound attitude has been taken by the authors in regard to high stress concentration at the T-head as revealed by the photo-elastic-determined stresses exhibited by Fig. 4—by neglecting them. At the highest concentrated stress of 5·6 times the average neck stress, it is seen that under normal conditions this stress would have a factor of safety upon ultimate strength of 1·45 to 2·16. Now, it is remarkable what large strains repeated very many times can be carried with complete safety, where there is a high concentration of stress. This fact is sometimes lightly explained by saying that plastic strain brings about a more favourable distribution of stress, but this makes only a minor contribution. The major factor is the ability of constructional steels to undergo cyclically repeated small plastic strains, "concertina" fashion, thousands of times without apparent distress or cracking. This property needs defining, but for the want of a better term it may well be referred to as "concertina" ductility, and it could be given precision by the conditions of test.

However, the fact is that constructional steels we have tested, which include black plate, are able to undergo a total strain of 0·3% when tested by bending in one direction—i.e. the applied strain is unidirectional—10 000 times without any visible signs of cracking. The equivalent elastic stress, as applicable for example to the stress concentrations of Fig. 4, would be 40 tons/in^2, although the ultimate tensile strength of the material is only just over 26 tons/in^2. Consequently, for the highest stress concentration shown by Fig. 4, and normal conditions, the factor of safety would be $(40 \times 1\cdot45)/26$ to $(40 \times 2\cdot16)/26$, i.e. 2·23 to 3·3. But it is very much greater than this because the machine is not likely to run away 10 000 times.

It is not sufficiently realized by mechanical engineers, and probably even less so by electrical engineers, that the yield point and ultimate strength of ductile steel is not a fixed quantity but depends upon the stress system operating. It has a specific value for simple tension, but if, for example, a tensile stress of one-half the magnitude were added at right angles, as occurs at the wall of a thin cylindrical tube under internal pressure, the yield point and tensile strength would each be raised about 15%, which would be the maximum increase obtainable on account of the stress system. The effects of combined stress are seen to some extent in Fig. 4, and also in Fig. 2, which indicates that the neck is literally a bottle-neck, with the minimum yield point occurring at about the middle of the length of the neck, where a condition of simple tension would exist. Clearly, to increase the running speed for the design, and to have the same runaway speed ratio, the yield point of the neck needs to be increased, and this could be brought about by thermal treatment without altering the factor of safety upon yield point. But also the factor of safety itself could be reduced without risk, and we believe a simply applied hydraulic proof-loading test could be contrived which would ensure, not only that something more than the maximum runaway loading had been applied, but also that the initial bedding-down and initial plastic-strain effects, which are evident in Fig. 3, were removed before the subsequent key tightening was carried out.

By thus concentrating attention upon the stressing of the parts—what the material can do, or be made to do—an increase of rating upon load of 20–25% appears within immediate reach. The rotor body, which presumably is not so heavily stressed, could keep pace by supporting a similar increase.

Dr. A. Mandl: There are two kinds of losses in the pole face: the no-load losses produced by the flux pulsation in the air-gap and the load pole-face losses. The m.m.f. in the slots produces a ripple in the m.m.f. curve at slot frequency. The pole-face losses on solid poles are therefore considerable. They are important only for the efficiency, and have little effect on the temperature rise. These losses can be reduced to about 50–70% by cutting circumferential grooves in the solid pole-face.

It is also possible to laminate the pole-shoe only and to hold the punchings with dovetails on a top plate which is either

* JOHNSON, E. M., and HOLDER, C. P.: Paper No. 1259 S, February, 1952 (see 99, Part II, p. 479).

integral with the solid pole or screwed down to it. This construction is useful for 4- and 6-pole machines, where sometimes poles and rotor body are in one piece. It has the tendency to a high pole-shoe and to a great leakage field between pole shoes.

The restrictions in the width/thickness ratio of the copper strap used for field coils wound on the Oerlikon machine are especially noticeable when the exciting voltage, and in consequence the number of turns per pole, is high. The fabricated coils do away with these restrictions. I should like to know how the joints are made.

The field winding of a salient-pole alternator represents an effective damper winding in the pole axis which has a small resistance but suffers from a great leakage. For all transient phenomena and for all disturbances on the transmission line it is desirable to arrange a symmetrical damper winding in the pole and quadrature axis. This can be done to a certain extent on rotors with solid pole-shoes by connecting these to each other on either side by copper rings. Good contact has to be provided, for instance, by tinning both parts before screwing them together. A further improvement is obtained by arranging a few strong copper bars near the centre of the pole-shoe.

The damper winding of a single-phase alternator has to compensate continuously the inverse rotating m.m.f. of the armature reaction. There are two main considerations for designing the damper cage: losses and mechanical strength. The heat transmission of the bare bars to the pole-shoe iron is excellent, so that a very high current density can be tolerated. The single-phase alternators built on the Continent for traction purposes are for $16\frac{2}{3}$ c/s. The current in the damper cage has a frequency of 33 c/s, so that the question of laminated bars does not arise.

A better compensation of the inverse rotating m.m.f. at lower losses can be obtained by arranging strong copper bars in the space between the pole-shoes.

In case of a sudden short-circuit great mechanical forces are exerted. The damper rings and the bars between the pole-shoes are especially exposed to them.

The former-wound complete coil in a 2-layer stator winding is among the best for this type of machine. Half-coils have to be joined at both ends in a way which does not interfere with the transposition of the conductors. The winding with half-coils is justified only if the size of the alternator and the output voltage are just right for a 2-layer winding with one turn per coil. The winding then consists of two bars per slot with transposition of the parallel wires inside the slot portion. The bars are connected solidly to each other to form complete turns or coils. The single-turn 2-layer winding with half-coils has two great advantages: the insulation between turns is at least the same as against the iron core and is therefore designed for the full voltage which is applied during the high-voltage test. It is also easier to replace a single bar instead of a single former-wound coil. The insulation of the soldered joints is, however, difficult.

A simple and effective way of transposing the conductor of a multi-turn former-wound coil in a 2-layer winding is obtained by dividing the copper in both directions, i.e. in depth and width. The nominal current density is thereby slightly increased. The division of the copper across the slot reduces stray losses which are produced by the main flux penetrating into the slot opening. These so-called main-pole eddies are not excessive, although these machines always have large air-gaps. They are greatly reduced if the conductor is split in width, and this nearly compensates for the higher I^2R loss.

The transposition of such a multi-turn coil is easily obtained by twisting the bundle of parallel wires which form one conductor 180° on one place in the end-winding. Each coil is self-contained, and the coil ends can be connected solidly to each other.

The coils are mica-taped over the whole length, or the slot portion is Haefely wrapped and the end-windings mica-taped. In the latter case a joint has to be made between these two insulations. This has to be well sealed to prevent surface tracking during the high-voltage test. The electric field density in air is high at the end of the core; it can be reduced by enlarging the stator slots in depth and in width on a short length at the end of the core so that the outer coil insulation can be thickened.

Mr. N. N. Hancock: Since it is customary to design the rotors of water-turbine-driven generators to withstand the stresses associated with runaway speeds, it would be interesting to know if such runaways ever occur. If they do not, such a practice is an unnecessary handicap in design and a cause of unjustified expense. Have the authors any statistics relating to the frequency of runaways? Again, if runaways are the result of governor failure, would not a system employing a simple overspeed trip such as is used on rotary convertors be feasible?

The statement that, with a properly transposed winding, strand insulation need do no more than ensure separation of the strands needs some qualification. It is true of both strand insulation and the insulation between turns that the electric stress is negligible under normal conditions. In both cases, however, under certain conditions, transient voltages far above the normal value can arise and cause punctures which may be difficult to detect until a major breakdown occurs.

The ratio of core length to pole pitch used in the preparation of Fig. 10 represents an advance on former practice, and I should like to know how it has been achieved and whether machines have already been built with such proportions.

Mr. P. J. Pollock: With reference to Fig. 4, the stress distribution in a plate of irregular shape can be calculated by means of Southwell's relaxation method. The process, although somewhat laborious, is straightforward enough.* The area concerned

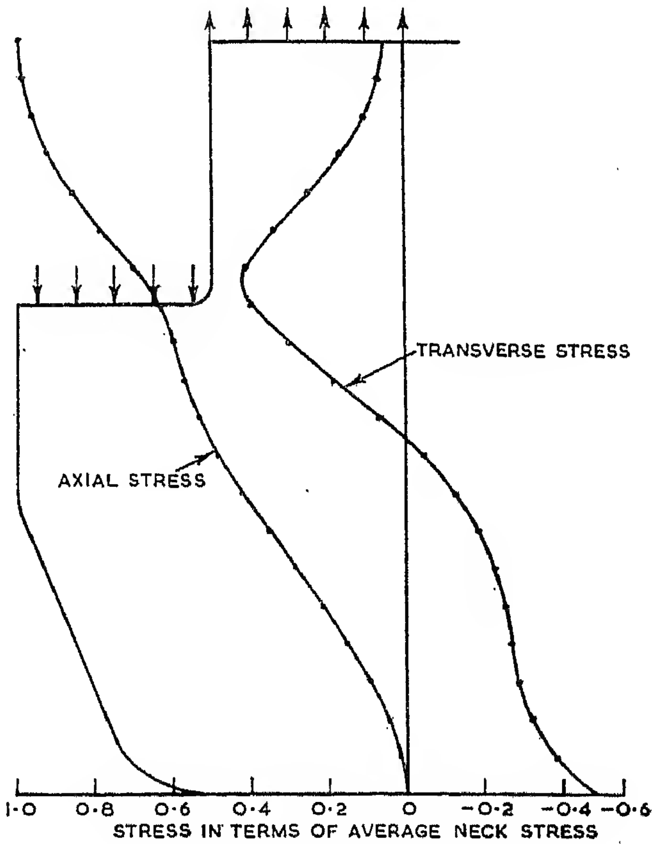


Fig. E.—Stresses on centre line of T-head.

is covered by a network of squares, and the differential equation, $\nabla^4\chi = 0$, to be satisfied by the stress function χ, is replaced by an approximation in finite differences. Values of χ are assumed

* SOUTHWELL and others: "Relaxation Methods applied to Engineering Problems, VII A," *Proceedings of the Royal Society*, A, October, 1945, 239, p. 419.

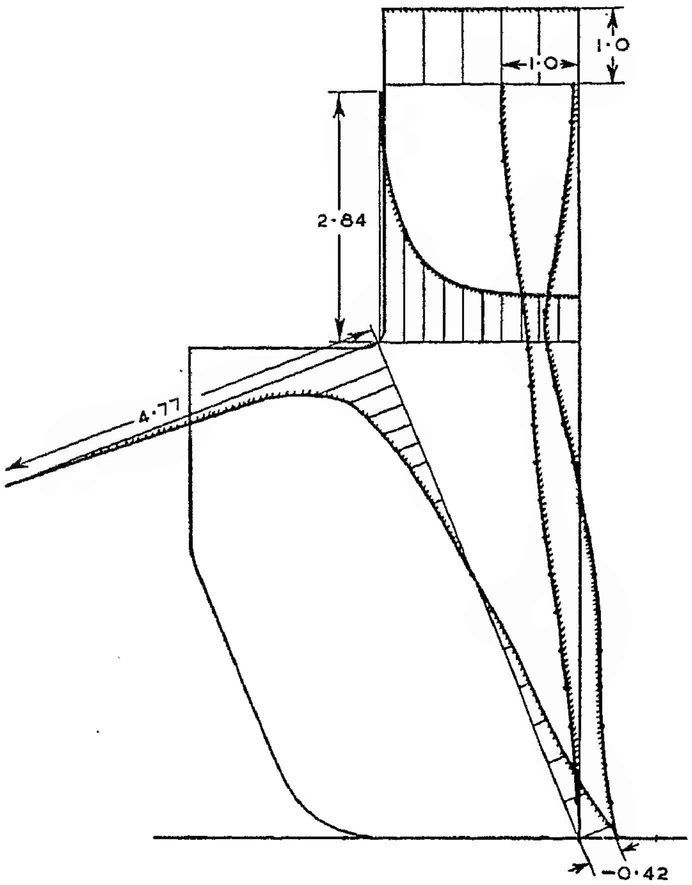


Fig. F.—Stress distribution in T-head in terms of average neck stress.

at all points and gradually modified until the equation is satisfied everywhere, to the required degree of accuracy. In parts where the stress is varying rapidly a correspondingly finer mesh must be used, and, since the stresses are given by the second differential of the stress function, the latter must be calculated to a higher degree of accuracy. Owing to symmetry only half the T-head need be considered. It is assumed to carry a uniform unit stress across the neck, Fig. E, balanced by an equivalent load uniformly distributed along the underside of the head. The Figure shows the calculated axial and transverse stresses along the centre-line. In order to make a comparison with Fig. 4 of the paper, these curves are reproduced on a smaller scale in Fig. F, together with curves showing the calculated stress components perpendicular to two of the sections indicated in Fig. 4. The results are seen to be very similar, confirming the intense local increase in stress near the fillet. The main source of difference is that in the photo-elastic test the load is probably not uniformly distributed, since bending of the sides of the slot causes the centre of pressure to move away from the axis.

Mr. J. Tudge: Referring to Fig. 4, it would seem logical as a basis for design to respect only the extrapolated bending stresses which can readily be estimated by analytical methods for short cantilevers and to ignore the fillet concentrations which would be relieved in ductile materials subject to steady stress. The authors have chosen possibly the strongest and most economical proportions for the T-head, but the depth of the slot lips would need corresponding adjustment to allow for different materials of body and pole if the same factor of safety is to be maintained. Further, with a laminated rim described in the authors' previous paper, that slot lip which is unavoidably near the edge of a segment and relatively more flexible than its neighbours carries little load. The increased load on the remaining lips for the worst case of two poles per segment is $33\frac{1}{3}\%$, requiring a corresponding increase in lip depth. Radial vent slots in the rim add even more to the load carried by the slot lips.

High-solidarity axial-flow fans can be designed to produce working pressures from 30–40% of the fan-tip velocity head. This may be considered unfavourable compared with centrifugal fans, but the radial outlet condition and the return path through the stator end-winding to the rotor interpolar spaces adds considerably to the resistance head of the machine, with the net result that more air can actually be delivered with an axial-flow fan at a much lower pressure, which is the primary reason for the low driving power required by these fans. Axial-flow fans, however, are more susceptible to constructional changes. An increase in fan-tip clearance from 0·1 to 0·3 in, for example, may reduce the air flow by about 15%, and an enclosed inlet which is popular on horizontal machines may reduce the air by 20% or more.

Mr. H. West: The fabrication of field coils is of interest in view of the advantages which accrue from this method of manufacture. Do the authors expect that brazed joints will always be used? Is it not possible that butt welding of the copper is worth considering?

The method of assembly described in Section 7.1 is of great interest, and it would be useful to know whether freedom from fretting corrosion is in any way due to the oil film which must be left in place after assembly when using this method.

Dr. Bailey has made some reference to the high stresses which can be accepted owing to the relieving effect of the plastic flow. It should be remembered, however, that where alternating forces are concerned surface defects become extremely important, particularly in places where high stresses are experienced. One should therefore be on guard against easy acceptance of localized high stress.

Mr. D. F. Milne (*communicated*): In discussing the principal insulation to stator coils, the authors draw attention to possible sources of weakness attending the use of Micafolium wrapping of the slot portion of the coil (Haefely process). They give the impression that they have not found this method entirely satisfactory, and as my experience has shown that the weaknesses of this method are very real, it would be of interest to know what advantages, if any, the Haefely process has over the end-to-end mica-tape wrapping, which appears to be the method favoured by the authors. Hydro-plant is particularly suitable for dealing with peak loads, and it is regular practice to run sets up to full load in a matter of minutes. Under such operating conditions the bitumen-impregnated mica-tape insulation is superior and preferable to the Haefely wrapping. Have the authors considered this point?

The authors describe an ingenious method of obtaining a heavy interference fit between the bore of the thrust collar and the rotor shaft which also permits of easy dismantling. The success of the method appears to be very dependent on obtaining near perfection in mating the tapers on shaft and collar, as the oil used to expand the collar would leak away if the tapers did not match and bed with great accuracy under the initial thrust of the forcing screws. The method offers no chance of the thrust collar accommodating itself to any alignment inaccuracy. Are any steps taken to ensure that the face of the thrust collar is perfectly true and square to the shaft axis after fitting, and can the authors be certain that the necessary accuracy will be maintained after the collar has been fitted and removed several times?

The method is said to have been developed to overcome trouble from corrosion fretting, which may occur with thrust collars that are a relatively easy fit on the rotor shaft. What has been the authors' experience with collars so fitted?

It is fairly obvious that fretting is caused by movement amounting to vibration occurring between the shaft and the bore of the thrust collar, and this vibration is most commonly caused by hydraulic conditions in the water turbine or by shaft-alignment errors. Permanently accurate alignment of the shaft in a 3-bearing vertical set is notoriously difficult to achieve, and it

would appear that a case could be made for having some measure of self-alignment at the thrust collar. The authors' comments on this statement would be appreciated.

The authors mention the advantages of the method of direct cooling of bearings in horizontal sets. I can endorse their remarks from experience with this type of cooling, which is used on the Tummel machines with great success. It is unfortunate that the vertical machine does not lend itself to similar treatment, as manufacturers might find it easier to keep the oil where it belongs. I have yet to see a vertical set which is free from criticism in this respect, and when, under "Ventilation," the authors mention the desirability of having a closed air-circuit to keep out dirt, I would like to suggest that it would be more to the point to keep out lubricating oil, as hydro-plants are seldom located in dirty atmospheres.

A good case can be made for open-circuit ventilation, particularly for plant intended for use in the Scottish Highlands and especially in remote-controlled or unattended stations. Getting rid of water pumps and coolers and the associated valves and pipework is a real step in improving the overall reliability of the plant. In the same way, anything which can be done to eliminate oil pumps and oil coolers is also worthy of close consideration.

In this connection it would be instructive to have the authors' comments on the respective merits of (*a*) non-circulating direct cooling of thrust and top guide bearings and self-lubricating bottom steady bearings using the Continental method of an oil bath with rifled oil grooves in the liner, (*b*) direct cooling of thrust-bearing oil with shaft-driven main oil-pump giving slow circulation of thrust oil and direct feed to bottom and top guide bearings, (*c*) the popular method in use to-day using external coolers with a.c.-motor-driven main oil-pump and d.c. starting and standby pump.

Of these three methods (*c*) is the least reliable, requiring a unit transformer connected direct to the stator, plus a good deal of external equipment in the way of oil and water pipes, valves, coolers and cabling. Other things being equal, (*a*) should be the most reliable, with (*b*) second. Incidentally, (*b*) is the method used at Rannoch power station, and it has given very good service now for 22 years.

[The authors' reply to the above discussion will be found on page 483.]

SOUTH-EAST SCOTLAND SUB-CENTRE, AT EDINBURGH, 12TH NOVEMBER, 1952

Mr. E. O. Taylor: The high overspeeds shown in Table 1 must impose a severe limit on the designer and add very considerably to the cost of this type of machine. Could the author say how often a particular generator is likely to attain such speeds; it is, presumably, likely to happen only if the governor gear fails at the time of a sudden dropping of the load. There are other safety devices available for preventing overspeed, and it is generally considered good practice to assume that if, say, three safety devices are fitted to prevent a disaster, they will not all fail simultaneously, and that the chance of the disaster occurring may be regarded as negligible. Would it not therefore be an economic proposition to spend money on the further development of such safety devices in order to save on the cost of the generators?

Mr. E. T. Metcalf: It may be of interest to illustrate one or two of the points discussed by reference to the 122 MVA 327 r.p.m. alternator which is mentioned in Table 1 and is being manufactured by the organization with which I am associated.

The rotor is designed to withstand a runaway speed of 610 r.p.m., the peripheral speed then being more than 30 000 ft/min.

The rotor body will be almost 14 ft in diameter and about 8 ft long, and each pole will be attached to it by a pair of tee heads. The weight of the body alone will be about 250 tons, while the total weight of the rotor, including poles and coils, will be of the order of 325 tons. It would be interesting to know whether the authors consider that the form of construction shown in Fig. 1(*b*), is really desirable when rotors reach dimensions of this order. One obvious problem is the accurate alignment of the shafts, which is essential whether the machine is horizontal or of the 2-bearing vertical type. In fact, a construction similar to that shown in Fig. 1(*a*) will be used, i.e. the plates will be shrunk on to a through-shaft, although this gives rise to a number of problems.

For instance, the temperature of the huge mass of steel which forms the body must be raised to about 150° C in order to obtain the necessary expansion of the bore, a procedure which may take at least two days, while a further week or more may be necessary for the plates to cool again.

Also, once such a hub is heated, the simplest method of inserting the shaft is to lower it in from above, but this has the disadvantage that the complete assembly is then upside down and must be turned through 180°. Turning over becomes a difficult operation if the hub is heavy and the shaft long, although it has been successfully accomplished for large rotors. For the 122 MVA set, therefore, the shaft will be located in a hole below the body while the latter is heated and will then be pulled up through the bore when this is sufficiently expanded, thus eliminating the need for turning over.

The thrust collar of the 122 MVA set will be very large, and the interference between collar and shaft will be about 0·0005 per inch of shaft diameter; for such a case the oil-injection method is of particular value and will be used. Experience has shown that by this method it is possible to fit large collars in less than a minute, a hydraulic jack being used to pull the collar up on to its seating. Removal is practically instantaneous unless the drop of the collar from its seating is controlled by the jack. If normal methods are used many hours may be required to carry out these operations.

Mr. W. G. Crawford: Figs. 2, 3, 4 and 5 give much interesting information on T-headed dovetails and should be compared with the T-head examined by Prof. Coker* in his classical paper on photo-elasticity, and with that described by Mr. A. D. Sloan† in his contribution to the discussion on the paper by Sir Charles Parsons and Mr. Rosen on the design of turbo-alternators. The T-head described by the authors is better suited to holding on alternator poles than are the other forms. The fact that a rationally designed T-headed dovetail always fails in the neck makes it very attractive to the normal draughtsman because the stress calculations are reduced to the simplest possible form. Against this there is the statement in the authors' previous paper that the 60° dovetail pressed in with a small interference fit is the strongest form. The design of such a dovetail requires careful consideration of the bending stresses, with an immediate increase in the complexity of the calculation. Many methods have been published for calculating bending stresses in 60° dovetails, but very few of them give results at all comparable with those obtained by Prof. Coker from photo-elastic measurements, so that great care is necessary in selecting a method of carrying out such calculations. The 60° dovetail produces a greater hoop stress in the rotor body than does the T-headed dovetail, and the final choice between the two types may well be influenced as

* Coker, E. G.: "Photo-Electricity," *Journal of the Franklin Institute*, 1925, 199.
† Sloan, A. D.: Contribution to discussion, *Journal I.E.E.*, 1929, 67, p. 1127

much by the stresses in the rotor body as by those in the dovetail.

When working with a factor of safety as low as $1 \cdot 5$ or 1 on the yield point of the material, a clear definition of factor of safety is necessary. The load/extension curve, Fig. 3, and the high stress concentrations shown in Fig. 4 indicate that there are considerable difficulties in defining the factor of safety. It might appear that the stress concentrations could be ignored as long as the material of the dovetail was sufficiently ductile to ensure that failure would not occur at the regions of stress concentration. However, Fig. 3 shows that the T-headed dovetail, in common with other complicated structures, has no well-defined yield point. Long before the structure as a whole is showing signs of plastic deformation there will be portions of it which are stressed to the yield point, and consequently the whole structure will be subject to a small but permanent distortion, so that there is the possibility of poles being slack after the overspeed run unless special precautions are taken. This risk can, of course, be eliminated by driving the wedges in so tightly that the dovetail is stressed to the yield point more or less as it would be on the overspeed run. If this is done, the dovetail will be subject to stresses, when stationary, which are comparable with those when running on the overspeed. This being so, it is clear that a definition of factor of safety which is based purely on the yield point of the material and the stress at overspeed is inadequate, and it would be most helpful if the authors would endeavour to give a more satisfactory definition of factor of safety.

Splitting the stator frame for ease of transport is a thing which no designer likes to do. Apart from the constructional difficulties which it introduces, it leads to difficulties with the stator winding, since it restricts the choice of winding. In a 14-pole machine the best stator winding for eliminating voltage ripples, according to Dr. Walker's paper,* requires an odd number of stator slots, and this immediately increases the difficulties in splitting the stator frame, since it increases the number of special stator segments in the region of the splits. To avoid this it is necessary to use an even number of stator slots and thus depart from Dr. Walker's ideal conditions of eliminating slot ripple. The fact that solid poles are normally used on this type of machine may help to counterbalance this in some measure.

[The authors' reply to the above discussion will be found on page 483.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 26TH JANUARY, 1953

Mr. J. Douglas: There are other methods of holding on the poles which have been used successfully by various Continental manufacturers, one example of which is to make a comb arrangement on the wheel and a similar type of comb on the poles, and to join these together by a series of dowel pins. This type has been used for many years by a Swiss firm, and I should like the authors' comments on its merits.

Another point is the design of the propeller fans. Recent developments on the axial compressors in a gas turbine have demonstrated that, where the fan has a fairly high solidity factor, the treatment of the blades as a cascade instead of the isolated aerofoil seems to give better results. The lift coefficient is higher. This is demonstrated in a recent volume on gas turbines and compressors by Vincent, who gives lift coefficients for the aerofoil, and for the cascade which shows that it is possible to obtain an appreciably higher coefficient when a cascade is used.

The authors have demonstrated in their bearing arrangement the most desirable condition of taking away the heat at close proximity to the point where it is generated and leaving the oil to be used for lubrication only. The simplification of this is enormous, as pumps with all their attendant complications are eliminated.

Another admirable point is the method of pressing on and taking off thrust collars and couplings by means of high-pressure oil. This is correct in principle and it ensures that the collar cannot move relative to the shaft.

Prof. J. C. Prescott: The authors refer to the effect of damper windings in reducing the effect of small pulsations of torque originating in the regulating mechanism of the prime mover, but they state that in the majority of cases the damper winding is not continuous round the periphery but consists of bars embedded in the pole-faces and connected by end-straps which extend only across the polar arc, there being no connection between the damper grids of adjacent poles. Such a damper would have little effect when the generator was operating on light load, and since this condition coincides with that where the damping effect of the water turbine is a minimum, I wonder whether any trouble has been experienced with hunting in the unloaded machine.

A trouble which sometimes presents itself in machines which are provided with dampers which encircle only the pole arc, the dampers encircling the interpolar space being omitted, is that they show on light load an inherent instability which was investigated by Bertram Hopkinson, and is sometimes called the Hopkinson instability. Such machines can have a negative damping coefficient, and even in the absence of periodic pulsation of applied torque can set themselves into oscillation. The effect may, in certain circumstances, be so pronounced as to make it impossible to operate the machine on light load in parallel with others. I do not know whether any manifestations of this type of instability have been noticed in the machines which the authors describe.

Mr. W. D. Horsley: While the trend in waterwheel development is towards larger outputs at higher speeds, the authors show in Section 9 that there is normally no difficulty in designing and building alternators to meet present requirements. They also demonstrate that increased outputs may be obtained by using aluminium in place of copper for the rotor coils. The possible advantages of hydrogen cooling have already been raised in discussion, but the authors did not indicate in their reply their views on the increase in limiting output, as distinct from specific output which would be gained by its adoption.

I agree with the authors' views that the slot portion of the stator coils should be covered with a semi-conducting layer to minimize corona, and that anti-corona paints are not necessary on the end windings, particularly as this may actually constitute a potential source of danger. It is, however, advisable to take steps to prevent corona where the conductor emerges from the end of the core.

The authors recommend that the first critical speed of a waterwheel rotor should be above the runaway speed, but indicate that it is not invariable practice to design for this condition. It would be of interest to know whether difficulties have ever been experienced when the first critical speed has been below the maximum overspeed.

Even if the critical speed of the shaft is above the runaway speed, it is probable that the combined critical speed of the shaft and supporting structure may be within the speed range of the rotor. On the other hand, the damping effect, particularly with a built-up rotor, may be high and any tendency to resonance damped out.

* WALKER, J. H.: "Slot Ripples in Alternator E.M.F. Waves," *Proceedings I.E.E.*, Paper No. 777 S, February, 1949 (96, Part II, p. 81).

Mr. P. L. Olsen: It is refreshing to learn at this stage in the industrial revolution that there is at least one mechanical contrivance that has not yet been pushed to its physical limits. This, I think, is the lesson that can be read into the merging of Table 1 into Fig. 10, although at least the 60 MW machine at 750 r.p.m. appears to be approaching the limits prescribed by the authors. Incidentally, it would be interesting to know what type of pole construction is adopted and what rotor conductor material is used, so that it can be related to its appropriate curve.

It may appear to engineers not conversant with generator design that the machines listed in Table 1 are not what might be called economical machines when compared with the limit curves. The assumptions on which the curves are based are quite normal, and I think it should be made clear that a similar specification applies to machines now in service and being built.

The paper summarizes clearly the design problems associated with large high-speed plant and deals in particular with the rotor pole fixing. This feature requires very careful consideration, and it is important that all known factors should be accounted for in the stress analysis so that the safety factor does not become an ignorance factor. In this connection, the tests on the pole fixings appear to be direct pulls on the T-heads and this suggests that the stressing is based only on centrifugal effects. It is appreciated that this is the only effect applying at runaway speed, but it will be interesting to know the extent of the effect of the bending moment exerted by the transmitted torque at normal speed. Would the authors suggest that over-speed chambers be provided for completed rotors of this class?

With regard to rotor coil clamps, do the authors consider that by special design these could give some relief to the stress on the T-heads of the pole? It is agreed that stator-coil replacement can be hindered by the use of coil clamps and they should be dispensed with if possible. Some form of locking could be incorporated in the section of the rotor strip to prevent side bulging, and this should not prove expensive with a fabricated coil.

The authors have wisely stressed the importance of the insulation joint between the stator slot cell and the end-winding taping, and point out that during assembly the joint may open out if not properly made. A more important point, however, is the effect of end-winding movement due to faults and surges in service which, as mentioned in Section 6.3.4, can be very severe. The opening of the joints should be precluded at all costs, as oil leakage is not unknown and a film of oil with brake-track dust is an ideal mixture for the instigation of tracking and ultimate breakdown.

One important feature in the design of bearing brackets is the allowable deflection. The design of the bearing housing, and in particular the details of the joints, requires careful thought to ensure that the joints do not tend to open when the bracket is deflected.

As mentioned previously, oil leakage from bearings does occur in these machines, and the bearing is inevitably on the suction side of the rotor fan, so that oil vapour is drawn into the machine, often with adverse effects. It would seem that external fans providing pressure air in the bearing zone would prevent this and at the same time enable a more satisfactory ventilation circuit to be arranged.

As the design of the braking system for vertical machines has not been referred to, it would seem that the higher peripheral speeds do not call for any modifications to existing methods. Perhaps the authors would confirm that this is so.

Mr. B. C. Robinson: The authors state in Section 6.3.2 that for surge protection they use a surge diverter coupled with a condenser. It is therefore presumed that both of these are connected to the machine terminals. It appears that the essential problem is to limit the maximum value of the surge voltage and the steepness of the incoming wave. The first objective may be achieved by a spark-gap in series with a non-linear-resistance type of surge absorber.

The steepness of the wave at the stator terminals is limited in the first instance by the characteristics of the machine winding, which only permit component frequencies below a certain critical frequency to penetrate the winding. This frequency is inversely proportional to the square root of the total inductance per turn of the windings. It may therefore be increased by increasing the inductance of the winding, and this would probably conflict with other design requirements. However, in some instances it may be found to give adequate protection, especially if windings with a single conductor per coil side are used.

The best method of lengthening the wavefront by external means is to connect a condenser or a length of cable to the winding terminal. The time required by this to change up increases the duration of the wavefront. This capacitance also absorbs the component of the incoming surge which is not accepted by the alternator winding, thus preventing the positive reflection of this component which causes a further voltage rise along the line.

The authors do not mention the protection from travelling waves in the winding by earthing the machine neutral either directly or through a low resistance. Since to obtain the best protection this should be less than one-third of the machine surge impedance, it would be helpful if the authors could give an approximate value for this parameter.

[The authors' reply to the above discussion will be found on page 483.]

SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, AT BIRMINGHAM, 9TH FEBRUARY, 1953

Dr. J. H. Walker: According to Fig. 10 it is possible to build an alternator with an output of 220 MVA at 428 r.p.m. A rough calculation based on a 14 ft gap diameter shows that 8 500 h.p. would be required to overspeed this machine to 770 r.p.m. An overspeed in a pit permits the rotor to be shrouded and the power to be reduced to a figure well below that of the motor usually installed in such pits. If, however, the dimensions of the rotor preclude testing in a pit, it may be necessary to run the rotor in its own stator; under these conditions experience shows that blocking of air inlets and outlets and other measures to reduce the windage loss have little effect. The supply of 8 500 h.p. then becomes a problem. To drive the rotor from its own exciter is out of the question, and the mounting of a motor on top of a vertical alternator presents difficulties. There remains the provision of a generator unit to supply the power at 90–100 c/s, the alternator being run as a synchronous motor; this generator unit would, however, represent a serious tie-up of capital, particularly in view of its infrequent use.

To avoid this impasse, various devices have been proposed for limiting the runaway speed of water turbines to a reasonable figure. However, the Swiss Electrotechnical Commission* recently reviewed all these devices, and their conclusion was that the necessary safety can only be obtained by subjecting rotors to the full overspeed test.

In the assumptions for Fig. 10 the authors quote a short-circuit ratio of 1·0. Since in these high-speed machines rotor heating tends to be limiting, a reduction of the short-circuit ratio

* *Bulletin de l'Association Suisse des Électriciens*, 31st May, 1952.

would bring some relief; if, combined with the use of a quiescent rheostatic voltage regulator, a short-circuit ratio of 1·0 is necessitated by line-charging requirements, then, with a reduced ratio and using a continuous-acting regulator, the required leading kVA could still be obtained. The latter regulator is capable of supplying negative field current, and this feature permits the leading kVA with a given short-circuit ratio to be increased by as much as 50% without danger of instability.

Mr. V. Easton: Since the fracture of the T-head securing the pole occurred in the neck and not at the fillets, it is clear that Figs. 4 and 5 are not representative of the actual stresses and that these in practice must be appreciably relieved by local strain. In Reference 2 of the paper it is suggested that mathematical analysis is not very reliable, so that one is left with tests on fairly massive specimens, such as those illustrated in Fig. 2. The method of indicating the strain in these test-pieces is rather crude, and it would be interesting to know whether any attempt has been made to obtain more accurate data. Incidentally, there is an error in Section 5.2.2, where the elastic limit of the neck material should read (45 000 lb load).

Fabrication of the field coils offers advantages in the elimination of the thickening of the inner edge of continuously wound coils, but at the same time great care is necessary when cleaning the joints after brazing to ensure uniform thickness and so to prevent local high pressure on the inter-turn insulation. It is not clear whether the authors use thinner strip to form the fins or whether they merely increase the width. The latter arrangement would result in a temperature of these turns appreciably below the remainder, and any attempt to take advantage of the lower mean temperature rise to increase the rating will result in greater heating of the normal turns and may introduce difficulties due to differential expansion.

It is surprising that difficulties due to creep of copper at class B temperatures have been experienced, and as an axial movement due to this cause would tend to draw the coils more tightly on to the pole, it would appear that any injurious movement would be tangential at the side of the coils probably on machines with few poles. Cases have been reported of fracture and axial movement of the insulating washer between the coil and the pole tips owing to the expansive force of the copper being transferred to the washer but not to the pole tips, which, in turn, is due to varying coefficients of friction between the various surfaces. A "slip plane" between the coil and the washer would limit the stress in the latter and should prevent this difficulty.

I agree that tapering the pole to eliminate coil clamps cannot be justified solely on the grounds of ventilation. If the taper is obtained by increasing the width of the pole-tip, the quadrature reactance will be increased and this in turn will reduce the stability, while if the pole-tip is unaltered but the root of the pole reduced, the flux density is increased in a place where saturation is already a limiting factor.

Referring to Fig. 8, it would be preferable to arrange the shroud at the base of the fan blades on a larger diameter corresponding approximately to that of the blade root rather than to one below the ring supporting the fan. The air would then have a smooth sweep through the blades, and the flow would not be upset by the radial component of velocity imparted to some of the air by contact with the outer end of the ring and the disc of the fan.

Mr. J. P. Huggard: Referring to the tensile test on a typical T-head shown in Fig. 2, the material used for the test is a very ductile low-tensile steel and not at all the sort of steel one would normally use with the type of high-speed machine which the authors have described. Has a similar test been carried out using the high-tensile steels which are usually associated with this type of machine, and are the results similar; i.e. are the high stress concentrations on the fillets shown in Fig. 4 similarly relieved on the high-tensile steels with much lower percentage elongation, and does failure occur on the neck as shown in Fig. 2?

In Fig. 10 the authors use the term "inertia constant H," but they do not state the units used. Are they using H to mean the kinetic energy in kilowatt-seconds of the rotating masses at normal speed divided by the full-load kilovolt-amperes, or do they mean the acceleration time-constant, i.e. the time in seconds to accelerate the rotating masses to full speed under full-load torque?

The possible outputs shown in Fig. 10 are very high, and when they are compared with similar curves shown in the Swiss article referred to in Reference 5, it is seen that these outputs, particularly curve $a'b'$, are very much higher than those shown in the Swiss article, in some cases twice as much. The basis of the Swiss article, and the constants used, seem to be similar to those used by the authors. Can the authors give an explanation?

Under "Insulation" the authors refer to the Haefely process of wrapping the coil with Micafolium. They are not quite fair to this process of insulating the coils when they say the drawback to this method is the joint between the wrapped cell and the taping at each end of the coil, and that it is necessary to use Class A insulation to make a satisfactory joint. There have been perfectly satisfactory joints made with this type of insulation for many years using Class B insulation throughout for voltages up to 22 kV, and I do not know of a case in which there has been a failure at that point. The Haefely process properly applied does give for the slot portion of the coil an insulation of higher electric strength than that provided by an equivalent insulation thickness of a completely mica-taped coil, and after all it is the slot portion of the coil which is most important.

Mr. A. G. Barton: Do the authors consider that hydrogen cooling would be an advantage? In Section 8 it is stated, "Tests have shown that dirt in a machine may increase the temperature rise on load by more than 10° C and it most certainly shortens the life of the insulation." I would have thought that hydrogen cooling, as used in modern turbine-type alternators, would have obviated this, and it might also obviate the use of fire-extinguishing equipment.

Mr. J. Ashmore: A matter which is of importance is the vibration problem. Would the authors please give some information about the balancing of these rotors?

Mr. G. Whiteside: I should like to raise one point following Mr. Easton's remarks. With reference to the corner joint shown in Fig. 6, could the authors say why they use the jig-saw design in preference to other types such as dovetail, etc.? The authors say that these joints are brazed. With brazing, using a filler wire, there is usually a surplus of metal; this would seem to me to present some insulation problem, because of high-pressure points at the joints, especially on the underside of the strip where difficulty might be experienced in cleaning away the surplus metal.

Mr. N. Griffiths: On large-diameter machines of the largest sizes mentioned in the paper, with comparatively large numbers of poles and solidified field coils, owing to the narrow pole angle, would not the coils be self-supporting without any coil clamps? It seems from theoretical figures that the tangential component of the centrifugal force is so small that the coil will hold together itself.

With the axial-flow fans, has there been any trouble with the ventilation of the stator-winding overhangs?

As axial direction is imparted to the ventilating air, how are the stator-winding overhangs effectively cooled?

Mr. J. G. Henderson: I should like to know what factors govern the choice between damper windings with pole-to-pole connections and damper windings without pole-to-pole connections.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. E. M. Johnson and **C. P. Holder** (*in reply*): The matters raised in the discussions are dealt with under Section headings.

Section 4.—The questions asked by Messrs. Hancock and Taylor in regard to overspeed protection are answered by Dr. Walker, quoting the Swiss Electrotechnical Commission.

Section 5.1.—Long experience with the type of construction illustrated in Fig. 1(*b*) has shown that Mr. Metcalf's fears are ungrounded.

Section 5.2.2.—Dr. Bailey's suggestion to proof-load the pole fixings hydraulically has interesting possibilities. We agree with him and with Mr. Crawford that current notions about factor of safety lack precision.

Mr. Pollock's calculations confirm, in general, the stress distribution shown in Fig. 4.

We are grateful to Mr. Easton for drawing attention to an error. The elastic limit of the material used for the tensile test occurs at a load of 45 000 lb, and not at a stress of 45 000 lb/in^2 as stated in the text.

Section 5.4.—Prof. Prescott is correct in saying that the effect of a discontinuous damper winding is poor at light loads. A recent investigation has shown that it may be advantageous for this reason to use a continuous damper winding in certain Francis-turbine applications.

Section 6.3.2.—Dr. Mandl, Mr. Milne and Mr. Olsen appear to support our preference for continuously taped stator coils. We agree with Mr. Huggard, however, that satisfactory coils are made using Micafolium wrap, but there is still a potential weakness at the insulation joint.

Section 7.1.—It is important, as Mr. Milne implies, that the face of the thrust collar should be normal to the axis of rotation. This can be achieved by a simple manufacturing technique. There is no reason why the initial accuracy should not be maintained.

We have not used loose-fitting thrust collars and have therefore no experience of the fretting corrosion which has been reported to arise from this cause.

A mattress of springs under the thrust pads provides a greater measure of self-alignment than a loosely fitting thrust collar. This subject was referred to in the discussion of Reference 1.

Direct water-cooling will be used in the thrust and guide bearings of four 138 MW vertical-shaft generators now under construction. We prefer this method to the others mentioned by Mr. Milne.

Section 8.—Experience in some remotely situated hydro-electric stations has shown that the "dirt" which it is desirable to exclude by closed-circuit ventilation includes insects, pollen and the like. This is particularly important where full-load operation takes place during the summer months. The Scottish Highlands may be exceptional in this respect.

The importance of protection against dust arising from constructional work should not be overlooked.

Section 9.—In reply to Mr. Huggard, the inertia constant H in Fig. 10 is expressed in kilowatt-seconds per kilovoltampere.

DISCUSSION ON
"DESIGN FEATURES OF CERTAIN BRITISH POWER STATIONS"*

NORTH-WESTERN CENTRE, AT MANCHESTER, 5TH MAY, 1953

Dr. W. H. Darlington: There is little to criticize in the paper, but the following comments may be of interest:

In Section 3 information is given regarding the condensing plant at Littlebrook. At the time when this condenser was being designed Mr. Bottomly was strongly influencing the condenser world by his paper on "The Economics of Condensing Plant": he insisted on a condenser rather larger than the manufacturers wished to build and having a circulating-water velocity through the tubes of 5 ft/sec. The condenser was finally built largely in line with his requirements, but subsequent experience proved that 5 ft/sec is rather too low, especially when cooling water—as at Littlebrook—has a lot of sediment such as mud in it. Normally the velocity under these conditions would be in the range 6–6½ ft/sec.

It can be seen from Fig. 2 that a supply of de-aerated condensate was made available during surge periods by introducing large-capacity tanks in the surge pipe coupling the low-pressure feed system to the surge tank.

The organization with which I am associated has tested this system and can say that it works extremely satisfactorily, figures of less than 0·01 millilitres/litre of oxygen being obtained consistently at the boiler feed-pump suction. Unfortunately, however, this system is very susceptible to any maloperation or falling-off in performance of the condensing plant. Any joint leakage, for instance, or porous castings in the extraction-pump suction or any leakage at the extraction-pump glands rapidly increases the oxygen figure, and this aerated water passes direct to the boiler without the benefit of double de-aeration, which would be obtained had a main de-aerator been arranged in the feed system.

It is now considered necessary for stations operating under steam conditions above 600–850° F to provide a main de-aerator in the feed line. This de-aerator can replace one of the high-pressure stages and will incorporate a capacity tank standing on the boiler feed-pump suction so as to render unnecessary the normal surge tanks; by this means double de-aeration is provided for all condensate going to the boiler.

It is noted that, at Cliff Quay, although the initial condensers were tubed alternately with aluminium-brass and cupro-nickel, the former material was not a success. It is, however, more interesting to note that cupro-nickel, which is the best of the commercial alloys at present on the market, is not entirely free from attack. In fact it would seem to indicate that it is very doubtful whether there is in existence at the moment a completely satisfactory tube alloy for either estuarine or heavily polluted waters.

The lessons which have been learned regarding high-pressure feed heaters at Littlebrook "B" have made it possible to obtain a correct appreciation of the value of high-pressure heater tubes from the maintenance point of view as distinct from the h.p. heaters in a modern high-pressure station.

I have been very concerned for some considerable time now regarding the quality of high-pressure feed-heater tubes received from the suppliers. During the early Littlebrook period any failure at a tube/tube-plate expanded joint was attributed to the expanded joint because, normally, all evidence was destroyed when the tube was drilled out for replacement or plugging. A careful inspection, however, has recently indicated that one of the types of tube defect which may occur is a split end, this being very difficult to ascertain by visual inspection. It may even on occasion not be found after expanding because the rolling of the metal sometimes tends to cover up the evidence. It is, however, an ever-present source of weakness and a possible source of leakage which in a very short time will enable high-pressure feed water to gouge the tube-plate so that it must be replaced. This is a very serious matter, since the present high-pressure feed-heater tube-plate is a very large and expensive forging, to say nothing of the man-hours involved in the detailed drilling.

My firm has for some time now been re-inspecting all tubes prior to assembly and has found a number of cases where tubes have failed on low preliminary water test. This problem of h.p. heater-tube quality is a most serious matter and every effort must be made to ensure some form of inspection procedure eliminating the human factor.

Even if this increased the price of the tubes it would almost certainly be worth while, considering the cost of having a large modern set with the h.p. heater out of service. This problem can undoubtedly be eased if split boiler feed-pumps are used so that the operating pressure on the heater tubes is correspondingly reduced. If, however, a customer insists on a single boiler feed-pump, then it is advantageous to arrange the h.p. heaters in twin lines so that the failure of the tube in a single heater does not jeopardize the main unit; the final feed temperature is affected only to a minor degree and the maintenance of the heater can be attended to as and when permitted.

It is realized that the paper is really a description of certain stations designed in conjunction with the organization with which the authors are associated and that the above remarks really apply to modern conditions, but they have been included since the work which led to these observations was brought about by consideration of the stations mentioned in the paper.

Dr. J. H. Bock: From the descriptions of the condensate and feed-heating systems in Table 3 and Fig. 2, it appears that all de-aeration is carried out in the condensers. Whilst this is adequate for low pressures, it is surprising that at Poole and Littlebrook "B" there are no separate de-aerators. Nowadays it is regarded as essential to reduce the oxygen content for high-pressure boilers to 0·01 millilitre/litre for the prevention of corrosion, whereas I understand that condenser makers do not guarantee figures below 0·03 millilitre/litre. Even if better figures can be obtained there is still the danger of oxygen entering the system, through condenser leakages, etc., which danger is increased with two-shift operation. I should like to know whether the authors would recommend de-aerators for new stations to-day, and if so, what de-aerator operating pressures they would employ.

I should like to know also the boiler-water concentrations maintained in the power stations described, and the authors' recommendations based on to-day's practice.

The authors state that, although it is preferable to mount boiler

* WHETMAN, S. D. and POWELL, A. E: Paper No. 1469 S, September, 1953 (*see* 100, Part I, p. 225).

feed-pumps in the basement, they are actually located at operating-floor level, and I should be interested to know whether this arrangement has been entirely satisfactory.

Littlebrook "B" is a reheat station designed for base-load operation. However, judging from the loading programme of the B.E.A., it may become necessary in the future to run reheat stations on a two-shift basis, or if this is impossible they might have to take load swings. For instance, during the lunch-time fall in load it might be necessary to reduce the boiler load by 50%, and the steam temperatures might then be so reduced that there would be a danger of the turbine rotor hogging. I should like to know what precautions have to be taken for this type of operation.

I should like to know the authors' opinion of the use of a house turbo-alternator for supplying auxiliary power, in order to make the auxiliary supply independent of frequency changes.

I do not understand why both gross and net efficiencies are quoted for the boilers in Table 6B. It is the accepted practice in this country to quote all boiler efficiencies on a basis of gross calorific value, and if a net efficiency is given it means the efficiency after deducting an allowance for the boiler auxiliary power consumption. However, from the figures in the Table it appears that the net efficiency means the efficiency based on the net or lower calorific value of the fuel.

At most of the stations described the boiler capacity seems to allow a considerable margin over the total steam requirements of the turbines even if one boiler is out of commission. This is a common design feature of power stations, but it makes steam temperature control more difficult at economic turbine loads and increases the cost of all boiler auxiliaries, and I should like to know whether the authors consider it really necessary.

Mr. G. Cooke: In Section 4 it is stated that the boiler feed-pumps are designed to give their rated output against full boiler blow-off pressure, and that the additional cost involved in basing the discharge pressure on the boiler blow-off pressure was small.

In deriving the feed-system characteristic, however, margins had to be allowed in the pressure-drop calculations which tended to elevate the duty point, and since margins were also added by the pump makers the result was generally to give a characteristic in excess of requirements. The margins for low-frequency operation were usually added on top of all this. A constant-speed feed-pump operated against the throttling of the boiler-feed regulator and there could be quite a loss of power, especially when the output was much lower than the design figure, owing to the difference between the pump head curve and the system characteristic curve. This was particularly so when several pumps were working in parallel, since under those conditions the full duty from each pump was seldom required. With a pulverized-fuel boiler the burners could be extinguished very quickly if the boiler was blowing off, and it therefore seems more logical to design the pump output for normal boiler pressure conditions.

The ideal method would be to vary the speed of the pump so that it could follow the system characteristic more closely, and one way of doing this was to use hydraulic variable-speed couplings. Since these appear to be coming into greater prominence I should be glad to have the authors' views on the general operating experience and desirability of this method of control.

In the same Section the authors refer to temperature-actuated leak-off devices for feed pumps, and state that they consider temperature control to be fundamentally correct. Whilst this may be true, the tendency is for feed temperatures to rise, which reduces the margin upon which a thermally-operated device can operate before the temperature of water in the pump reaches the point where serious overheating takes place. Usually the time between the rise in water temperature and complete failure is extremely short.

I think that a device related to flow of water from the pump would be more satisfactory. The output of the pump would be metered and when this fell below a predetermined point the leak-off valve would be automatically opened; it would close again as the pump output rose. I believe that this method is the subject of a patent in America.

With regard to high-pressure pipework the authors have stated that the adoption of economic pressure drop would result in much higher steam velocities, etc. I think insufficient attention has been given to the determination of economic pipe sizes. With the increasing use of unit systems, i.e. one boiler to one turbine, where no pipe mains system is involved and actual steam flows can be determined more closely, there is a very strong case for a proper economic study.

With regard to the pulverizing equipment, there is a tendency nowadays for the mill feeders to be located at the mill itself instead of at the firing floor. The mill feeder is the principal point of control for the pulverizing plant, and whilst I can see no serious objection I should be glad to have the authors' opinion concerning this latest tendency.

Mr. J. L. Ashworth: In Section 3 it is stated that the fitting of turbine supervisory gear on the 2-cylinder machines operating at moderate steam temperature at Cliff Quay was considered an unnecessary expense. There is not yet sufficient experience of this equipment in the country to lay down precise rules, and this position is clearly indicated in B.S. 132. At the present time it is fairly common practice to fit supervisory gear to turbines of 50MW or larger capacity. The tendency is to link the need for the equipment with the size and temperature of the turbine.

Turbines are temperamental and each machine has its own individual characteristics. There are machines fitted with the equipment which are handled satisfactorily and with confidence by the operating staff without reference to the indications of the supervisory equipment, and other machines of equal size and temperature conditions where the operating staff completely rely on this equipment for successful operation.

Many medium-size machines without supervisory gear operating to-day on base-load or near base-load conditions will, in the not too distant future, be relegated to 2-shift operation. Frequent stopping and starting may reveal unsuspected troubles which might seriously affect availability. I suggest that portable turbine supervisory gear could be a valuable aid in those circumstances where the expense of fitting permanent equipment to each machine is not justified.

On a supply system where the night load is small in relation to the day load, quick starting and loading have important economic considerations, and I was very interested in the figure of 4·04% extra losses of 2-shift operation compared with continuous load given in Section 9 for the plant at Earley. 2·17% appears to be directly attributable to the turbine and emphasizes the desirability of rapid starting.

Comparison of the starting times for Poole 1 and Poole 3 seems to indicate the confidence felt in the supervisory gear. At Kearsley power station considerable progress has been made in rapid starting on a 52 MW 3 000 r.p.m. turbine with steam at 600 lb/in² and 800° F at the turbine stop valve. A typical "run up" after an overnight shut-down is as follows:

Run up to speed and synchronized	17 min.
Loading to 52 MW	49 min.
Total time from stationary to full load ..	66 min.

Two important points with regard to rapid starting are (*a*) temperature of turbine metal, and (*b*) temperature of incoming steam.

After the turbine is shut down the bottom half of the casing cools more rapidly than the top half, and there may be quite an appreciable difference in temperature between the two halves at

the commencement of the "run up." An attempt to reduce this difference was made on a 30 MW 3 000 r.p.m. machine at Carlisle by fitting a sealing plate underneath the h.p. turbine.

Before the sealing plate was fitted temperature differences of 80–90° F were normally obtained between the top and bottom halves of the casing of the h.p. turbine. After the sealing plate had been fitted no appreciable temperature difference could be detected.

Mr. F. Marshall (*communicated*): On the question of boiler feed-pump leak-off, I agree with the authors that temperature control is fundamentally correct, and I should like to suggest that where a bled-steam de-aerator is included on the suction side of the feed pumps it is essential that the leak-off be controlled by the differential temperature across the pumps.

I should like to ask the authors what prompted the decision to adopt 825° F for the temperature of the reheat steam at the Littlebrook "B" station, as against the generally accepted principle of reheating to the initial steam temperature. Was it an economic decision to enable carbon steel to be used in the boiler reheater and the associated pipework?

With regard to the necessity of a quick start for stations on shift operation, I notice in Fig. 15 the remark "Admit water to h.p. inlet and l.p. glands." I think the authors will agree that the adoption of steam sealing on all glands is an essential design feature if a turbine is likely to be worked on shift operation. I should like to have the authors' opinion of working a reheat station such as Littlebrook "B" on shift operation. Is the plant flexible and can the whole plant be brought up with the reheater in service?

Mr. A. M. Thyer (*Tasmania: communicated*): In view of the differences between the plants, some information as to their overall and sectional and capital costs would be of value to those engaged on power-plant design.

Some information on experience as to the necessity of the margins provided and their effect on the cost would also be appreciated.

It is felt that the operational data and availability figures quoted do not give a very clear picture of the operational experience because of the limited time covered. An extension of this information over a longer period would be of value, particularly concerning the time between necessary boiler cleaning and deterioration of performance in service; also data as to maintenance of firing equipment, particularly in respect to the Littlebrook plant, which has the highest furnace loading.

With regard to the turbine plant, it is noted that in certain cases devices are fitted to obviate troubles due to loss of load, and it would be interesting to know whether load-rejection tests have been carried out and, if so, with what results. In such a test, do the relief valves on the intermediate-pressure system at Littlebrook lift?

Fig. 1 has created some comment, particularly as to the function of the ordinate scale and the reason for the differing efficiencies at 80% of the machine with the maximum efficiency at that rating and at 100% in the case of the machine with full-load economic rating.

Information on the types of butt-welded joints used for the piping, and experience with them both from a constructional and from a maintenance viewpoint, would be appreciated.

[The author's reply to the above discussion will be found on page 496.]

MERSEY AND NORTH WALES CENTRE AT LIVERPOOL, 19TH OCTOBER, 1953

Mr. W. H. C. Pilling: First, I think that the elimination of the feed-pump bays as such is an important development for two reasons—it saves a bay, which is of course an important consideration in building costs, and it avoids the introduction of a subsidiary means of handling the feed pump. I was particularly interested because this has been done in one or two stations with which I am associated and use has been made of the space saved by placing the auxiliary switchgear for the whole station in that bay; in the more usual layout the turbine house auxiliary switchgear is alongside the turbine house with the boiler-house gear at the back. The modified arrangement has considerably simplified the cable runs and has saved building space.

The other general point which interests me is that from Table 1 it would appear that in the development of these five stations, which were designed immediately before and completed after the 1939–45 War, a very similar method of development was used as is being followed by the British Electricity Authority to-day, namely that three of the five stations are what one might call "routine" stations, with comparatively low pressures and temperatures, and the other two are of more advanced design.

In Section 3 of the paper, the authors have compared the relative merits of sets with the most economical rating at 80% and at 100% of maximum load. I feel that there they have understated the case for the machine having an economic rating of 100% from the high-pressure-cylinder casting point of view. Defective castings are very prevalent and any simplification of design which assists castings should be encouraged.

Again in Section 3, the authors refer to the fitting of a device to assist the governor to act rapidly in shutting off steam in the event of sudden loss of load. Would they not consider it better to concentrate on the design of a governor which will perform its proper function without such assistance?

In Section 4, I assume from the authors' description that the Littlebrook "B" arrangement is typical of the others. I should like to ask whether effective de-aeration of the feed water has been obtained. I am rather surprised that it has not been found necessary to install a de-aerator with—in the case of two-shift stations—provision for storage of de-aerated water when starting up.

In the same Section it is noted that pre-treatment of raw-water make-up before evaporation is by lime-soda softening. Has this method of treatment been found to be fully satisfactory? In my view hydrogen-ion/sodium-zeolite blend pre-treatment would reduce the amount of sludge and scale in the evaporator and the residual carbon dioxide in the pipework.

I note from Table 4, on boiler plant, that in one case pendant-type superheaters have been installed. I should like to ask the authors for their views on the relative merits and demerits of the pendant and the self-draining types of superheater. Two alternative methods of superheat temperature-control have been adopted—one by gas by-pass and the other by desuperheater. Has experience indicated a preference for either method?

I notice that the authors have suggested that it has not been found necessary to use to their full extent the 2-section air-heaters which are installed in the majority of the stations, and I think they would agree with me that the adoption of the 2-section heaters leads to a very complicated arrangement of ducting.

Again, I should like to ask the authors whether the results at the stations which they have described give any indication as to the relative merits of tubular and plate-type air heaters, and whether they have a prejudice against the regenerative type. I notice that in not a single one of their stations has the regenerative type been fitted.

I am very interested to note that the adoption of water-cooled furnaces has led to difficulties in the type of ash plant which has

been adopted at some of these stations. Similar troubles have been experienced at a station in this area. The return of dust to the clean-water reservoir has been dealt with in this case by pumping the dust-laden water to a settling reservoir and returning the clear water to the system. The plant to which I refer incorporates a system of belt conveyors for taking the ash and dust to barges, and there has been considerable spillage from these conveyors.

In Table 4, I note the reference to hydraulic control of soot blowers at Blackwall Point, and I should like the authors' views on this method and to know whether they would advocate it in preference to electrical control—which I think everybody would agree is complicated and requires specialist attention for maintenance.

Was any difficulty experienced in arranging segregation of electrical controls in the hydrogen control cabinet (Fig. 8) to the satisfaction of the Factory Inspector? At one station with which I am associated the design of the hydrogen-purity indicator with an intrinsically safe electrical circuit presented some difficulty. The authors refer to the use of bearing oil for shaft sealing in an emergency. Have they considered using oil from this system for sealing under normal running conditions?

As to Section 8.4, I should like to draw attention to the importance of arranging the instruments on the panel so as to give the maximum assistance to the operators. Essential instruments referring to minute-to-minute control of the plant should be emphasized, the remainder taking up secondary positions.

I was surprised to note from Figs. 15 and 16 (Section 9) that the h.p. shaft eccentricity is checked at 400 r.p.m., whereas the alternator critical speed is somewhere in the region of 1 400–1 500 r.p.m. I should have thought that a clearer indication of excess eccentricity would be safely obtained at, say, 800–900 r.p.m.

My second comment on Section 9 is on outages at Littlebrook "B" (Table 6C), where the milling plant appears to have given more trouble than elsewhere. Have the authors any explanation for this?

Finally, could the authors explain the five outages due to high eccentricity of turbine shafts at Littlebrook "B" (Table 6C) when only one case of thermal instability at this station is mentioned in Section 9.4?

Mr. V. L. Farthing: It is interesting to note that a silencer was not used to reduce the noise from the high-pressure steam leak-off and that a multi-holed orifice was found to be satisfactory. Were these plain orifices or was some kind of ejector principle used?

The now well-established method of demineralization was used at Poole for boiler feed. As a matter of interest I would call attention to a new method of water treatment of fire-tube boilers and evaporators by ultrasonics, the invention of a Swiss engineer.

No mention is made of the very important matter of ash disposal or of the important use to which ash is now being put in the chemical world.

Under the heading of "Generators" mention is made of excess solvent in the insulation varnish causing trouble at Littlebrook. This, of course, can also be a contributory cause of oil trouble in transformers. No mention is made of the method of filtration of such oil.

Mr. D. A. Picken: There is a point in Table 5 which illustrates particularly commendable practice: the design of installations so as to reduce the fault levels to the very low values quoted not only greatly reduces the cost of the switchgear, but also, in the event of a mishap or short-circuit occurring due to the reduction in fault energies, the injuries to any person in the neighbourhood will be very much less. The practice of using large transformers of low reactance in connection with installations is to be deprecated, and it is noteworthy that in these five installations which are associated with h.v. fault currents in the neighbouring systems it has been practicable to design to such a low level.

Mr. J. Eccles: I suppose that the British Electricity Authority for some time to come will not have to design as many peak-load stations as base-load stations, since, as a station design becomes superseded, the older stations will naturally be called upon to do the peak-load work and most of the newer plant will be required for base-load purposes. This is not wholly true because the peaks are there and for these very high thermal cycles and very large sets it is impracticable to shut the sets down overnight. I think there will in the future be scope for some moderate size peak-load units, but for the time being there is a fair amount of that plant in the existing stations.

If you want a very low pressure drop for a given length of pipe you have to increase the diameter, and with the bigger pipe size there may be considerable trouble due to end thrust, which, in turn, is due to expansion. Have the authors considered multiple pipes? Much thinner walls are required for a given steam pressure with a 3 in pipe than with a 12 in one, and, of course, it is much easier to do the crochet work with a battery of 3 in pipes than with 12 in pipes.

In Section 5 there is a statement that "to accelerate the erection programme it was agreed that the first section of the pipework at Poole should be constructed with the intermediate joints also flange seal-welded; but from technical considerations it would have been better to have adhered to the specified butt-welded joints." Later in the same Section, with reference to Littlebrook "B," it is stated that "all joints at valves are of the flanged and bolted seal-weld type and have given no trouble." If they have given no trouble at Littlebrook "B," where the conditions are much more strenuous than at Poole, what is behind the earlier suggestion that it would have been better to adhere to butt-welded joints?

Mr. F. J. Worland: I was rather surprised by the authors' remark that ash plants do not affect the availability or thermal efficiency of power stations, and that they did not therefore propose to refer to ash plants in the paper. Ash plants do affect the thermal efficiency and availability of a boiler, and I should like the authors to expand their statement.

The thermal efficiency can be affected by the quantity of water that is introduced for quenching, where that method is used for refractory preservation or safety, and by the amount of extraneous air that is admitted to the ash chamber during the removal of the ash. The availability of a boiler is affected by the life of the linings of the ash hopper, and if the ash-removal plant failed the boiler could not be kept on full load for more than a day or so, unless its evaporative capacity was low.

Mr. R. Ecker: We know from Fig. 1 that, within limits, different efficiencies may be designed into steam turbines.

Using Blackwall Point test figures for guidance (from Table 6B) we find that 9 235 B.Th.U./kWh in Fig. 1 at the 80% load of the lower curve would go up to about 9 400 B.Th.U./kWh at the 100% load for this curve, and not 9 475 as shown by the curve. Thus both the machine of 80% maximum economic rating and that of 100% maximum continuous economic rating, selected for presentation, may have the same—or approximately the same—heat rates at full load, i.e. 9 400 B.Th.U./kWh. This cannot be achieved with the same frame (assuming good design, of course) and it cannot therefore be true that these curves represent essentially the same machines, except that one is with and one without a by-pass valve. What in fact seems to be the case is that a high-efficiency machine of 80% maximum economic rating and a low-efficiency machine of 100% maximum continuous economic rating are being compared.

In order to arrive at what would seem to be a more realistic comparison in Fig. 1, I have used the Bromborough machine as

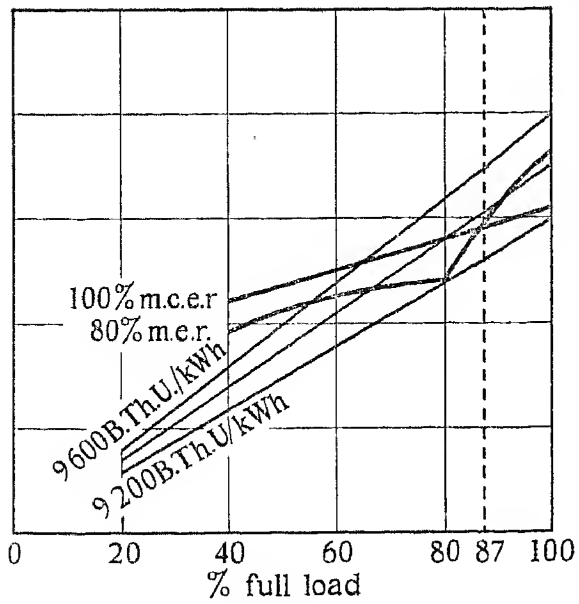


Fig. B.

the basis of some estimates (see Fig. B). This is a 900 lb/in^2 50 MW maximum-continuous-economic-rated machine, and all units of that design have recently been tested and shown to give better performance than guarantee, which is of the order of 9 200 B.Th.U./kWh. By fitting a by-pass to that machine and making it 80% maximum economic rating with a better vacuum, the estimate shows that at 100% load this new machine would have a heat rate about $2\frac{1}{2}$% worse than the Bromborough one. The improvement at 80% load on that machine by comparison with 80% load at Bromborough would be in the order of 2% and not 4% as shown in Fig. 1. This would have the effect of moving the authors' 93% line to about 87% as the limit above which the turbo-generator of maximum continuous economic rating is more economical in British thermal units per kilowatt-hour than the comparable machine of 80% maximum economic rating.

I agree with the authors that the overall economics of machines of maximum continuous economic rating and 80% maximum economic rating must be carefully studied with each new project. One of the items which would have to be taken into account in such calculations would be the increased reliability of high-temperature machines in the absence of by-pass valves, and possibly better rates of loading these machines when starting.

Finally, on the subject of acceptance tests (Table 6B), I would say that No. 2 and No. 3 machines on Blackwall Point have been tested after some months' service and for that reason failed to reach the excellent performance of No. 1 machine by about 1%. Even so, taking account of the different cycle conditions, excluding boilers and auxiliaries, Blackwall appears to be the most efficient turbine mentioned in the Table. I wonder whether the authors could tell us to what extent these different machines have come up to their expectations and how they compare between themselves.

Mr. R. S. Atkinson: On the matter of cooling water, it appears that in spite of the study of an analysis of the cooling water to be used, serious problems still arise after stations have come into operation, and the condenser-tube troubles experienced at Cliff Quay are a case in point.

My experience has been that stations using water from large rivers and estuaries have individual problems which either were not foreseen or could not be foreseen during the design stages. Stations quite close together on the same waterway could have, and do have, totally different problems.

It therefore seems that there is scope for the development of an adequate technique to ensure (*a*) that water will be abstracted with the minimum amount of solid matter in suspension, (*b*) that an adequate clean channel will be maintained in the river bed to the water intakes, and (*c*) that the effect of the water on the condenser tubes, particularly in relation to erosion and corrosion, should be solved in advance.

The authors point out that plant at Littlebrook "B" would probably now be designed with one boiler to each turbine, in view of the advances made in boiler manufacture since the station was designed. However, the operational experience gained at Littlebrook, of which I have had some personal experience, has clearly shown that there is no serious difficulty in operating two reheat boilers in parallel on one turbine unit.

The omission of a dividing wall between the turbine room and boiler room at Littlebrook "B" has facilitated close liaison between the plant operators in each section, and I suggest that this might be considered as the initial step in combining the control and operation of unitized turbine and boiler plant under one highly skilled operator who could have the instruments and controls necessary for the operation of the whole plant grouped in one location suitable sited. If necessary, the observation of furnace and similar conditions could be provided for this operator by means of television. In the case of furnace observation, the development of full colour television would undoubtedly be an advantage.

I suggest that this method of operating high-cost high-efficiency plant would ensure, by the use of a technically qualified operator, that maximum possible efficiency was obtained at all times.

I agree with the authors' contention that there is no real case for expending capital on extra steelwork merely in order to put boiler feed-pumps at operating-floor level in order to keep them under the observation of the senior operator. Whilst feed pumps are undoubtedly an important auxiliary, their reliability is sufficiently good to justify placing them at basement level, where they would receive at least an amount of supervision equal to the other important auxiliaries already located there.

One important feature incorporated at Littlebrook "B" was an additional pulverized-fuel mill per boiler with an output of only 6 400 lb/hr. This small mill has proved invaluable for lighting-up purposes and has avoided the extensive use of oil otherwise necessary owing to the instability of burners associated with large mills when firing at very low rates. It is suggested that there is scope for the development of small pulverized-fuel milling plant designed primarily for lighting-up purposes and pressure raising on large pulverized-fuel boilers.

The high thermal efficiency attained at Littlebrook "B" over a prolonged period is confirmation of the high efficiency of the reheat cycle when using even quite moderate steam temperatures, and it is somewhat disappointing to see that wider use of this heat cycle has not been made in this country, particularly in view of the extremely difficult and worsening position in the supply of British coals.

[The authors' reply to the above discussion will be found on page 496.]

WESTERN SUPPLY GROUP, AT CARDIFF, 2ND NOVEMBER, 1953

Mr. B. S. Gylee: I have observed from the paper that it had been general practice to install the turbo-alternators longitudinally in the turbine room. I would like to point out that this method of installation gives rise to a very unwieldly plant to operate, particularly for the charge engineers, who are required to give attention to the whole plant. I should like to know whether there is any good reason for abandoning the transverse installation of these machines, which I consider reduces the length of

the turbine room and gives a more compact plant for operational purposes.

I notice from the paper that, in one or two cases, gravity-bucket conveyors have been used. Is it not time that this most undesirable piece of plant should be eliminated from power station practice, particularly bearing in mind that operation in this industry is necessarily on low grades of small coal, for which gravity-bucket conveyors are most undesirable? Would it not be a good thing if architectural requirements were properly weighted in relation to engineering practice?

Lastly, I would like the authors' opinion on the necessity for supplying steam-driven feed pumps in modern pulverized-fuel-fired boiler layouts. In my experience, automatic-starting steam pumps do not in fact start automatically, and they are not installed in such a manner that their operation is efficient. They are never vitally necessary for such a plant, and I consider that the capital tied up in such equipment could be better spent to the advantage of the operating and maintenance staff in better designed equipment elsewhere.

Mr. E. Hywel Jones: In Section 5 there is a reference to flange seal-welded joints at valves or the alternative use of bolted joints. These very often prove to be a weak point under operational conditions and the joints have to be re-made merely because they leak and not because access is required to the adjacent valves. It would be better to provide butt-welded joints and be prepared to cut through them and re-weld on the rare occasions when access to a valve is necessary.

When a station is designed on the unit system, particularly if two-shift working is likely to develop in the future, it seems desirable to provide a much wider range of steam temperature control than is the practice at present. It is possible to run a set up to speed in a relatively short time and without undue worry regarding expansion as the steam temperature tends to rise gradually during the running-up period. Once on load, however, it would be a distinct advantage to run for an hour or two at a reduced steam temperature whilst the set was warming up and adopting its working clearances. This method has been used by the Americans and has enabled the loading-up process to be greatly quickened.

With regard to instrumentation, the operating engineer is almost always at a disadvantage with new plant because the complete instrument boards are not commissioned for some time after the turbo-alternator sets or boilers have come into service. Under the present system this is almost inevitable as a large mass of small wiring and fine pipes have to be connected into position after the plant is installed. The difficulty might be overcome to some extent if—particularly in the case of turbo-alternators—a very simple panel was designed to be installed adjacent to the set containing the bare minimum of instruments required for the operator to control the machine. Every effort should be made to have this panel ready before the machine is run up for the first time. At a later stage the more elaborate instruments could be accommodated on another panel a little further away from the set in a position chosen to give the best possible access to the instruments and protect them against possible transmitted vibrations. Whilst these secondary instruments would be a useful refinement to the control of the machine, there would be no difficulty in securing reasonable operation during the weeks or months whilst the second panel was being commissioned.

[The authors' reply to the above discussion will be found on page 496.]

NORTHERN IRELAND CENTRE AT BELFAST, 10TH NOVEMBER, 1953

Mr. H. Weston: I am intrigued by the authors' opening claim that the design principles of the stations concerned are correctly based on good practice or special circumstances. This is a very astute statement, for it will always enable them to evade an argument; e.g. I presume that if we criticize Earley for its unit circulating-water pumping system it will probably be pleaded that the plant was originally intended for South Africa. Do the authors not now think it would have been preferable to adopt a busbar system and to dispense with vacuum-controlled pay-off gear? Up to now we have always viewed this appendage with a certain amount of distrust. Do the authors know whether it has ever operated out of its turn?

The choice of the relatively conservative steam conditions for Blackwall Point is not very clear, even though the sets are of 30 MW capacity. The explanation offered is that these conditions, which were chosen in 1945, were based upon an anticipated low load-factor. Yet in the same year the choice for Poole was 900 lb/in^2 and 925° F, where again a high load-factor was not anticipated and where in fact the running load-factor is some 6% below that of Blackwall Point. It seems that 900 lb/in^2 and 925° F would have been a better choice for this station, or can it be inferred that conditions at Blackwall Point were chosen, not only because of a low load-factor but also because of the possibility of two-shift operation; and, if so, do the authors think that 900 lb/in^2 and 925° F conditions are unsuitable for two-shift operation?

Can we be told the additional cost per kilowatt of plant installed that the extensive foundation work at Poole involved, and was there any piling carried out between the sheet-steel girdle?

I am in full agreement with the authors' preference for a by-pass type of machine irrespective of size. I think it must be almost impossible to forecast a fixed loading throughout the life of any particular installation, and from the moment that a forecast proves untrue there will generally be a lowering in the overall performance of the non-by-pass machine. However, whilst the inclusion of a by-pass valve undoubtedly increases the intricacies of high-pressure cylinder design, can the authors confirm that troubles have been experienced due to variations between cylinder and spindle temperatures caused through the use of a by-pass valve? It seems to be so important to install plant having an 80% economic rating that serious thought should be given to discouraging the manufacturers' drift away from the use of the by-pass valve.

It is rather unfortunate that all the boiler plants described are for pulverized fuel, and the paper would have been more representative if at least one example of modern stoker-fired plant could have been included, especially since the authors' statement that the 3-drum bent-tube type of boiler is representative of present-day practice may not necessarily be correct where a stoker-fired boiler is concerned. Comment on this would be appreciated. I believe, too, that it would have been interesting to see how stoker-fired plant would have shown up in Table 6C. To those responsible for continuity of supply this Table is possibly the most important one in the paper, and it is significant that plant outages increase as pressures and temperatures increase. A total of seven outages due to turbine-shaft eccentricity is disconcerting, and the authors give no guarantee that, having passed a thermal stability test, freedom from future trouble is assured.

Table 6C makes no specific reference to air heaters. Can it therefore be assumed that these have been immune from trouble? If not, what troubles have been experienced, and how do the tubular and plate heaters compare? Blackwall Point's final gas

temperature of 255° F seems to be dangerously low, especially for tubular heaters, which are expensive and difficult to renew.

Finally, I suggest that the authors have made one very important omission. In no instance have they given the cost per kilowatt of the plant installed. Admittedly they can plead that site conditions must affect such costs, but I think they would have been very useful and informative.

Mr. W. Szwander: Standardization of power station design is making continuous progress, and, in that respect, the five stations described in the paper constitute a good example of the trends noticeable throughout the world. Great caution, however, is advised in applying generally developed standards to individual cases, such as, for example, that of the Northern Ireland power system, which is small by comparison with the British Grid receiving power from the majority of power stations now being equipped by the British industry. On account of that system size difference, reliability requirements in respect of individual sets and boilers in the Northern Ireland stations are naturally greater than in the B.E.A. stations; hence such solutions as, for example, the one boiler per set arrangement, or oversimplification of the auxiliary power-supply systems and of steam and feed-water connections, are not acceptable here. Also many refinements and elaborations, made in the interests of increased reliability here (e.g. in the sphere of protection and control) elsewhere considered unnecessary, may have very sound economic justification. It has been our experience in Northern Ireland (where, until now, a number of 33 kV wound generators are in service) that lately the manufacturers appear to prefer 11·8 kV generators with 11·8/33 kV unit-connected step-up transformers; could the authors confirm that this is at present a general trend? Similarly, numerous generators are now being arranged in the British power stations to feed direct into the 132 kV Grid system; the time is not too distant when also the Northern Ireland 110 kV Grid may have to take supplies direct from generators. In this connection the universally adopted station auxiliary system (Fig. 11) has the disadvantage of the high cost of the 132 kV (or 110 kV) connected station transformers. This problem may be solved by relying on unit transformers only, with a scheme of connections* making possible the starting and supplying the general station auxiliary services from unit transformers of the running sets. In the light of experience gained outside Great Britain it appears regrettable that in British power stations the operating rooms are still being treated largely as switchgear and electrical output control centres only, instead of being given their proper character of full station operation control centres, which would require their location between the turbine and boiler house, with both the turbine and the boiler control panels accommodated in them.† From observation of construction progress of new power stations, one cannot avoid being struck by the tremendous quantities of structural steel being used to satisfy three only indirectly essential requirements: that of providing a building to enclose the whole station, that of keeping thousands of tons of coal in bunkers high above the firing aisle, and that of supporting the turbine-house crane capable of performing the very infrequent task of lifting the generator stator. While any departures from long-established practices always ask for much courage and foresight, it appears that the above observation shows the way towards the possibility of drastically cutting down the complication, the cost and the construction time of the power stations of the future.

Mr. N. Berry: From all we read about power-station sites there appears to be none available except those whose value increases out of all reason when their projected use is known, and in consequence difficulties of planning are undoubtedly increased.

With regard to circulating-water systems, unless special circumstances demand the use of unit pumps, the advantage of using the buspipe system and thereby obtaining a flexible arrangement for economy, convenience of operation and for maintenance, has much in its favour.

In connection with chlorination of the circulating water, I should be interested to learn whether the introduction of the chlorine is made with the sole object of keeping the condensers clean, or whether it is to keep the inlet culverts and screens clear also. Serious difficulties with screening plant can arise where the chlorine is added regularly to keep down growth in the culverts, and more information on the effects of such dosing would be useful.

The authors do not appear to have mentioned whether any provisions have been made for the maintenance of pure steam and feed-water conditions. Even when only small amounts of gases, such as carbon dioxide or ammonia, enter the system over a period, the concentrations can build up quite appreciably, even with make-up de-aeration, and I should like to know how these concentrations could be kept to a minimum. One method is to bleed the system via the ejector third-stage drains, but this has the disadvantage of increasing the amount of make-up water required.

With regard to operation of feed-pump leak-off valves by temperature control, I should be interested to learn whether further experience has shown this arrangement to be sufficiently reliable or whether any back-up to it has been found necessary in order to keep losses to a minimum and avoid serious results to the feed pump in the event of its failure.

Mr. T. F. Ross: The authors considered supervisory gear unnecessary on the Cliff Quay machines, and my own experience of turbines with similar stop-valve conditions, provided with supervisory gear, seems to bear this out. I would be most interested to hear how the Littlebrook "B" and Poole machines behave when running up, particularly in relation to shaft eccentricity.

With regard to hydrogen cooling, I think the advantages associated with the system outweigh the disadvantages. One advantage claimed, however, is that it is possible to increase the output of the alternator considerably by raising the hydrogen pressure. For this to be possible, the turbine must have a correspondingly increased capacity. Bearing in mind the remarks about overload valves, can this be arranged economically?

I understand the latest American standards recommend the adoption of hydrogen cooling for all alternators of 16 MW capacity and upwards, whereas the British practice seems to be from 60 MW and upwards. Is this again only a matter of economics?

[The authors' reply to the above discussion will be found on page 496.]

RUGBY SUB-CENTRE, AT RUGBY, 17TH NOVEMBER, 1953

Mr. C. D. Palfreyman: Table 5 summarizes the electrical equipment, and it will be seen that in the particular stations mentioned, where the generators are coupled direct to the 132 kV Grid, the main switchgear is of the air-blast or low-oil-content impulse type. This information might be misleading to an engineer not familiar with current practice in this country because the ordinary bulk-oil circuit-breaker is still very much

* Szwander, W.: "Generating Station Auxiliary Services—Improved Scheme of Power Supply," *Electrical Review*, 1948, 143, p. 421.

† Szwander, W.: "Control in Generating Stations," *Electrical Review*, 1950, 147, pp. 219, 311, 459 and 555.

in demand. It should go on record that, of all the power stations erected since the war where generator switching is carried out at 132 kV, nearly one-half employ the bulk-oil circuit-breaker for this purpose. No doubt you are also familiar with the lenticular oil circuit-breaker now being installed in some of the 275 kV substations on the super-Grid.

While on this question of switching generators at 132 kV, it is interesting to note the authors' comments on the reasons for this choice contained in Section 8.1. The inference to be drawn here is that the major factor governing the voltage at which generators are switched is the necessity for limiting the fault power on the system, but it is not always economic to step-up and step-down the voltage in order to keep down the short-circuit rating of the switchgear.

Switchgear can be designed and built to much higher ratings than at present, and in America they have found it necessary to develop switchgear to deal with this problem. For instance, some of their ratings are as follows:

MVA		kV
3 500	at	69
10 000	at	161
15 000	at	230
25 000	at	330

These figures show that switchgear can be designed for any system fault-rating, and the same considerations could apply in this country. For example, the fault rating of the 132 kV Grid system was 1 500 MVA at the start; it was later increased to 2 500 MVA, and now circuit-breakers are being supplied with a rating of 3 500 MVA. It is not unreasonable to assume that circuit-breakers with a rating of 5 000 MVA or even higher may be required in the not-too-distant future.

Therefore, I think it will be agreed that there is another reason for connecting generators direct to the 132 kV Grid, namely that the 132 kV system is becoming a distribution network, and the B.E.A. are selecting the most suitable sites and building generating stations solely for the purpose of feeding power into this network.

Referring again to Table 5, it will be seen that air-break switchgear has been employed in most cases for the auxiliary circuits, the larger motors being supplied at 3·3 kV and the smaller machines at 415 volts. The notable exception to this is the Littlebrook power station, where a voltage of 6 kV has been used for the main auxiliary switchgear.

This voltage is rarely used for station auxiliaries because there is no suitable air-break switchgear available at the moment, and it is generally understood that the use of 6 kV motors is not justified economically. If, for these reasons, 3·3 kV is the preferred voltage, the larger stations may require the main auxiliary switchgear to have a fault rating of nearly twice the present level. I should like the authors' opinion on this matter.

No comments are given on the method of earthing the neutral points of the auxiliary systems. There is a very good case for connecting the neutrals solidly to earth, although at Poole power station, I note from Fig. 11 that fuses and voltage-transformers are employed for this purpose.

At the present time, a lot of interest is being shown in the question of standardization owing, no doubt, to the increasing influence of the B.E.A. One of the items under discussion between the manufacturers and the B.E.A. is the arrangement of instruments and controls for generator circuits. Not only have the number and type of instruments to be settled but also their disposition as between the control panel and the alternator control-desk. I believe finality has now been reached in this matter and the proposed standard agrees with the arrangement of apparatus mentioned in Section 8.3. In the proposal, it is laid down that for unit sets a steam-pressure gauge is required to be mounted on the generator control panel. In this connection I endorse the authors' view that the pressure gauge should be omitted from the control panel, because the information it gives can be obtained very readily by other means, and there is no point in confusing the control-room operator with any more than the essential indications. I would also like to know whether the machine designers have been consulted in regard to the general question of instrumentation.

In the United States, it is becoming fairly common practice to combine the controls of the boiler, turbine and alternator on one set of panels. Sometimes one or two sets of such panels are located together in a plant control-room which can be situated at operating level between the boilers and the turbines. This practice is supposed to give rise to increased operating efficiency, although it may lead to staffing difficulties. I should like to have the authors' views as to the desirability or otherwise of adopting such an arrangement in this country.

[The authors' reply to the above discussion will be found on page 496.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 23RD NOVEMBER, 1953

Mr. W. Dixon: As regards Littlebrook "B," I cannot help feeling that the performance of this high-pressure reheat station must be a source of secret satisfaction to the operators of Dunston "B" 2. With a cycle operating at twice the pressure, it ought to have a "sent out" heat rate substantially better than Dunston.* In fact the heat rate is only slightly better, although the test results on the turbo-alternators and the boilers at Littlebrook "B" show that the product of the efficiencies of these two is in accordance with expectations. It is true that in 1952 Littlebrook "B" did attain the best overall efficiency, but it is hoped that further efforts will secure even better results.

A further point is that, although a good deal of expense was incurred in bringing the level of this station to + 20 ft O.D., and therefore above flood level, it was in fact flooded, in common with other stations on the south bank of the Thames, and had to be shut down during the disastrous flooding early this year. I think it should be made clear that the flooding occurred, not through the river banks immediately in front of the station, but from breaches of the river wall east and west of the station, and that the water entered the basement of Littlebrook "C," then under construction, through the incomplete retaining wall at the south end, and ultimately flooded the basements of "A" and "B" stations via the basement interconnection. The completion of the "C" station will naturally bring with it the restoration of complete flood protection as originally designed.

Turning now to the method of construction of the foundations at Poole (Section 1.4), I have frequently heard criticism of this on the basis of additional cost. If, however, it is realized that when work was started you could row over the site at high tide and that in parts silt was over 40 ft deep, it will be clear that the first essential was to obtain space on which to work, and it was eventually decided to enclose a large area, dig out and replace with a cover to obtain a solid and reliable foundation.

The possibility of piling was considered as an alternative, but this method was not adopted owing to anticipated difficulties, and expensive though it was, there is no doubt that the method described and adopted was correct for this particular site.

* Howell, A., and Jackson, J. B.: "The Design and Operation of Dunston 'B' Generating Station with particular reference to 50 MW Turbo-Alternators Unitized with Re-heater Boilers," *Proceedings of The Institution of Mechanical Engineers*, 1953, 167, Part A, p. 81.

Reference has been made to large ocean-going colliers being able to come alongside at Cliff Quay, which also applies to Littlebrook and Blackwall Point. At Poole, however, owing to depth restrictions at the bar to Poole Harbour, the colliers are smaller, having a maximum capacity of about 2000 tons. Earley is, of course, entirely dependent on rail-borne coal.

I hardly need add that the coal delivered to the respective stations is seldom in accordance with that in the original specifications.

Finally, a point that stands out from the paper is the apparently random distribution of machine size which is rather striking in comparison with present-day uniformity in Great Britain. It is worth remembering, therefore, that the present situation in England is exceptionally favourable to the adoption of widely spaced standards. Formerly when the national control was more operational and when operating costs still had to be compared with fictitious independent operation, there was still some real advantage in matching new generation plant to the requirements of one's own system, either company or municipal. Furthermore, it still remains for someone to show the precise effect of standardization on the price of a turbo-alternator or boiler, as distinct from the acknowledged convenience to the manufacturer. It goes without saying that convenience to the manufacturer should result in the long run in lower price and quicker delivery, but what in fact (even now) is the difference to the purchaser in cost per kilowatt between a 60 MW standard machine and, say, a 50 MW for the same steam conditions, and how much quicker would delivery be? Nowadays one does not need to consider this matter so carefully for plant in this country, but formerly, and oversea even now, this question was and is of real importance.

Mr. S. G. Weeks: I feel that modifications to the furnaces at Earley were necessary, because low-volatility coal is provided, whereas the furnaces were designed for high-volatility coal. At Cliff Quay, modifications were made in the opposite direction. Refractory surfaces in the furnaces were removed because the furnaces, designed for a less volatile coal, are in fact being fired with a high-volatility coal. Wherever possible the B.E.A. should arrange for supplies of coal to suit the furnace design and so avoid modifications after a boiler has been erected. It is appreciated, however, that the B.E.A. are not able to choose with complete freedom the coal they require.

From the starting-up curves shown in Figs. 17 and 18 it is apparent that at Earley steam is admitted to the turbines at saturation temperature, whereas at Blackwall Point steam is not admitted to the turbines until it is superheated by about 250° F when starting up. There is a good case for a measure of standardization of turbine starting requirements, and this would assist the boiler operators and manufacturers. At Earley the starting-up practice must be of considerable help to the boiler operators, since these boilers are fitted with non-draining superheaters.

In Section 5 the authors have referred to both radiographic and magnetic testing of welds, and they appear to favour to some extent the radiographic method. In my opinion certain types of defect are difficult to detect with radiographic examination, and magnetic testing might in some cases give more complete results. I also suggest that in the near future the use of ultrasonic gear may well prove of considerable value on this type of work.

I should like to draw the authors' attention to their statement that the Cliff Quay furnaces were in the initial stages completely refractory-block lined. This was not the case; the extent of initial refractory surface in the Cliff Quay furnaces is indicated in Fig. 4 by the dark line on the furnace side walls: there was also an area of refractory at the top of the front walls. The comments on the gas by-pass adjustment at this power station are perhaps misleading, since the gas by-pass dampers can, of course, be adjusted during boiler operation.

[The authors' reply to the above discussion will be found on page 496.]

SOUTHERN CENTRE, AT PORTSMOUTH, 2ND DECEMBER, 1953

Mr. E. W. Connon: I should like to refer to the methods of neutral earthing which have been used in some of the stations mentioned in the paper. It has been the practice of the designers of these stations to earth the neutrals, not only of the generator-transformer combination, but also of the 3 kV and 415-volt auxiliary systems, through some combination of a voltage transformer, a fuse and a spark-gap. For the generator-transformer combination a voltage transformer alone has often been used, but at Poole we did not feel that this arrangement was satisfactory and an arc-suppression coil was substituted. Since this time, further experience and discussions have led the B.E.A. to standardize upon resistance earthing for the neutrals of generator-transformer combinations.

With the 3 kV and 415-volt system, the designers of these stations described have again used fuses and/or voltage transformers for neutral earthing. Now these systems are in effect distribution systems, and it would be interesting to have a full appreciation of why the practice in generating-station distribution systems has become different from the practice in distribution systems for public supply where customarily neutral earthing is either solid, by means of a resistance, or effected by an arc-suppression coil.

Mr. A. Abbott: It will be noted from Table 5 that the voltage of the auxiliary switchgear at Earley is 3·3 kV whilst that specified for Blackwall Point, Cliff Quay and Poole is 3 kV. The reason for this I believe was that at that time there was some doubt about the performance of air-break switchgear at the standard voltage of 3·3 kV at 150 MVA short-circuit capacity; it was a question of rupturing the full short-circuit current; thus to be on the safe side in specifying a 3·3 kV switch to operate satisfactorily at 3 kV the manufacturers had to test it at a short-circuit current of 28·8 kA instead of 26·2 kA.

At Meaford station an oil circuit-breaker is inserted between the generator and the l.v. side of the step-up transformer; it is thus possible to omit station transformers and their associated switches and interconnecting cables, etc., the machine auxiliaries being started up by leaving open the l.v. switch, closing the h.v. one and then synchronizing on the l.v. switch.

It is considered practicable to substitute a load-making remote-controlled isolator instead of an oil circuit-breaker between the generator and the step-up transformer: this could be mounted close to, or upon, the machine foundation block. Perhaps the authors could explain why the Meaford layout has not as yet been developed further in this country, although I believe a number of such layouts have been installed abroad.

The most reliable supply of electricity in a power station directly connected to the Grid is the Grid.

Had this layout been adopted at Poole, for instance, the capital cost of electrical equipment would have been reduced by approximately £110 000 excluding civil costs, which might amount to the saving of another £10 000, and on the advice of experts I am told no serious limitation in operation would result.

With reference to Section 7 the separate excitation method at Cliff Quay and Littlebrook has given good service, and I believe has not been detrimental under system fault conditions.

The geared exciters necessitate a long overall shaft-length, thus

requiring more accommodation per set. A further point is that any untoward vibration on the machine may have repercussions on the gearing which, even at intermittent periods, might in time create wear with consequent increase in noise. However, for machines in excess of 60 MW the direct-driven exciter becomes a relatively large high-speed d.c. generator, a device discarded about 30 years ago.

One way out of the difficulty might be to install a direct-driven a.c. generator on the main shaft coupled direct (electrically) to a low-speed motor-generator set—this maintains the unit principle, and it should be remembered that after the power transformer a slow-running motor-generator set has proved over a period of years to be a most reliable piece of electrical equipment, and the maintenance costs are negligible.

Finally on the matter of switchgear (Section 8), I note that Blackwall Point and Cliff Quay were considered marginal cases for 33 kV generation.

It seems to me that as the Area Boards build up concentrated load at this voltage near to an intended new station or proposed extension to an existing one, 33 kV generation may have to be taken more into consideration. The experience at Earley with generators at this voltage has up to the present been quite satisfactory.

As regards auxiliary switchgear, where only air-break is used, I do not think it necessary to house it in separate switch-houses, as is the case to my knowledge at four of the stations mentioned in the paper. The fire risk is negligible, and the amount of dirt and grit, etc., in a modern station is very small, even where pulverized fuel is used. It is sound practice in my view to erect the gear open to the turbine room, thus saving the cost of dividing walls, etc.

Mr. S. R. Arnold: In Fig. 10 the supply network of Littlebrook station is shown, and I note that the 66 kV network in the Orpington area is fed by means of star/star wound transformers. What method of reducing the effects of third-harmonic currents is employed, no tertiary windings being evident as at Poole (Fig. 11)?

Adverting to mechanical matters, the authors remarked that it was not the custom to include the power consumption of auxiliary plant in the station heat balance. This is a pity, since it means in practice that little attention is paid to improving auxiliary efficiency. For example, most coal conveying, elevating and bunkering plant is worm-reduction-gear driven, tests of which have shown it is little more than 40% efficient after a few months of use. A 60 MW station of my acquaintance has coal-raising plant using 7 200 kWh daily, i.e. approximately 0·4% of the output. Could this not be greatly reduced by double-reduction spur gears now available at very nearly the same price? Again, it is customary to drive the governor-relay lubricating oil-pumps of large turbo-alternator sets by worm gearing. Would this be taking more power than is generally suspected? Also, could not greater use be made of aerodynamic knowledge to improve draught plant layout? Considerable power must surely be wasted in overcoming the friction set up by the many sharp bends and changes of duct section apparent in the examples shown.

It is noted that both air heaters and economizers are used in all the cases described and that the precipitators occupy considerable space as well as providing a large heat-dissipating area from their casings. Could a case be made for dispensing with economizers? Further, the low gas velocity needed to effect acceptable precipitator efficiency might be necessitating a higher chimney entry temperature than is advisable in the interests of efficiency. Recent tests in connection with another type of prime mover have shown that much greater precipitator velocities are possible if this device is placed in a higher-temperature zone.

Finally, the question of recovering the alternator losses now the sets are becoming so large could no doubt be re-opened with advantage. Hydrogen combustion air-heat exchangers developed from chemical plant knowledge are reliable devices nowadays, and could be incorporated with advantage in the draught plant.

It seems that integration of all these points could make a considerable and acceptable reduction in the electricity used in power stations.

[The authors' reply to the above discussion will be found on page 496.]

WESTERN CENTRE, AT BRISTOL, 11TH JANUARY, 1954

Mr. F. Thomas: Do the authors consider that the extra complication and capital expenditure of employing a reheat system is warranted for two-shift stations?

It is noted that in all the five stations described, either tube or plate air-heaters are employed; it would be interesting to know whether regenerative heaters were considered since they occupy less space.

Mr. J. Irlam: On a number of occasions I visited the Poole site during construction, and in the early days I was struck by the massive and costly nature of the foundation works for the station proper; were methods other than the construction of the girdle wall, and complete excavation and concreting within, investigated during the early consideration given to the foundation design? I have in mind the ground-freezing process, well known in civil engineering circles, and the construction of heavy sleeper walls designed to carry all plant and building loads either longitudinally or across the axis of the station. I think such a system might have shown economies over the one adopted.

The old generating station at Feeder Road, Bristol, which was constructed on a marsh with hard founding at 35 ft below ground level, was constructed on the wall principle, the walls being tied at ground level by a massive reinforced-concrete raft; the spaces between these walls were used for culverts and storage water tanks.

Mr. A. C. Thirtle: The particulars given in Table 1 show the serious effects of the war period on our technical advancement in generation design. Although some courage was shown in adopting a pressure of 1 235 lb/in^2 at Littlebrook "B" with a reheat cycle, the temperature of 825° F was very conservative in the light of known experience of 950° F working in the United States. It now appears regrettable that more courage was not displayed by both consultants and manufacturers as well as the C.E.B. in the large programme of plant which had to be put in hand immediately after the war period. The excessive lapse of time between design and commissioning dates in this country is a costly handicap.

The heat-consumption curves shown in Fig. 1 are most interesting, although the comparison of 80% and 100% ratings does not appear to be realistic for all types of turbine steam-admission control. With the greater use of the transmission system it appears to be more economic to design the larger sets for 100% economic rating and to operate them at full load when on the busbars. To obtain the full benefit of such running, the time taken when starting and running up to full load must be brought to a minimum. What are the authors' views on the improvements over the results shown in Figs. 15–18 for present-day designs? No. 1 set at Poole, in Fig. 15, shows 60 min for running up and a loading rate of 2 MW/min. A later design of this manufacture has a shorter overall turbine shaft with a solid forged l.p. rotor solid-coupled to the h.p. spindle. It is hoped that this design will give improved performance in this

respect. Can the authors say what we could expect as minimum times for starting and loading of new 60 and 120 MW sets?

Section 4 refers to a new technique for water purification in the demineralization plant at Poole. Very satisfactory results have been experienced with this plant, and all make-up is provided therefrom without the use of evaporators. If such plant can be 100% dependable, would it not improve the cycle efficiency if the cold demineralized make-up were sprayed into the turbine exhaust immediately above the condenser? I am not certain from Fig. 2 whether this cold make-up is introduced into the condenser at a high enough level to act in a small way as a spray condenser.

I should like to put in a plea for greater attention to auxiliary plant design. Table 6C shows the serious effect of such items as economizer caps and milling plant on the availability figures of Blackwall Point and Littlebrook "B."

Mr. N. Higginson: The paper refers to the adoption of turbine overspeed anticipatory gear at Poole, Cliff Quay and Littlebrook "B." It is appreciated that overspeed will obtain only with loss of load coincident with a machine becoming disconnected from the main electrical network.

Could the authors say whether, in their experience, machines of 30 MW and above, not fitted with this feature, are unable to meet the British Standard requirements for turbine speed-governing on loss of bulk load?

The authors refer to the more likely incidence of falling vacuum with unit-operated circulating-water pumps. This is also the case with certain stations when, at a certain period of the year, river-borne blanket weed causes sudden fouling of the main inlet water screens.

Whilst the use of automatic load paying-off equipment with consequent reduction in l.p. cylinder overheating and atmospheric relief sizes appears to be advantageous, I am interested to know whether there is any risk of turbine "gulping" on restoration of vacuum from, say, 25 in to 29 in, between which values the "speeder run-back gear" is not put into operation.

It would have been interesting if the authors had included more details of the types of auxiliary drives. Table 4 indicates 2-speed motor-driven induced- and forced-draught fans with damper control.

Damper control appears to be rather an inefficient method of draught control compared with inlet vane control—particularly when automatic combustion control is adopted. I believe that the higher initial cost of variable-speed fan drive by means of scoop-controlled (or equivalent) couplings, or variable-speed motors, can be justified within a few years in the savings made in electrical energy consumed, and I should like to know the authors' views in this regard.

In view of the trend at the time, it is interesting to note that, with the exception of Earley, direct generation at 33 kV was not adopted for certain stated reasons. Did the effect of the rather preponderant third-harmonic voltage which varies between no load and full load in the range 500–1 100 volts with 33 kV generators also have any bearing on the decisions?

[The authors' reply to the above discussion will be found on page 496.]

SOUTH-EAST SCOTLAND SUB-CENTRE, AT EDINBURGH, 19TH JANUARY, 1954

Prof. R. O. Kapp: One of the thoughts that this paper raises is how progress in power-station design in this country is hampered by the great length of time that elapses between planning a station and setting it to work. Progress must proceed step by step. For one cannot risk a major departure from given steam conditions and established designs until some working experience has been gained with these. In other countries the time interval between steps is not great and progress can be proportionately more rapid than it is in this country, where the interval is very great. Taking a long view, this consequence of the time-lag between designing and being able to test the design in operation is, in my opinion, more serious than the large amount of idle capital tied up during the construction of a station.

It is appropriate, as we are assembled in Edinburgh and are considering power-station design, to remember Portobello. The arrangement there, which Mr. Field initiated when he was Chief Engineer of the Edinburgh Corporation Electricity Department, consists of one 540 000 lb/h boiler to each 60 MW turbo-alternator assembly. This assembly is made up of two turbines, each with its own 30 MW alternator. The whole is controlled by a single circuit-breaker. I feel sure that such a unit arrangement, with one boiler to one generating assembly, is economically and technically sound practice for present conditions. This equipment appears third in the published efficiency tables for 1951–52.

It is interesting to consider what the present technical limits for steam conditions are likely to be. Stations are already planned with temperatures up to 1 050° F. Such a temperature is probably the best, economically, at the present time, for it does not call for unduly expensive steels; the best ferritic steels, such as molybdenum-vanadium, are suitable, except perhaps for components exposed to particularly corrosive conditions. But long-term policy demands that we should build a few stations unhampered by economic considerations and regard the extra cost as large-scale and very valuable research. It seems quite likely that within the next few years stations in this experimental class will employ temperatures up to 1 450° F. Niobium-stabilized austenitic steels that would withstand such temperatures are already available.

The heavy cost per kilowatt of modern stations makes availability of very great importance, and this leads me to ask whether it would be safe to reduce boiler outages required now by the Factory Acts. It is worth remembering that the requirements of the Factory Acts are designed to make all boilers safe, including the worst cases such as small installations operated by unskilled labour and fed with make-up water very different in quantity and quality from the 2% of distilled water put into power-station boilers. Some valuable concessions have been made already, but research into the rate and manner of boiler deterioration in modern power stations might well show that further concessions could safely be made.

Lastly I should like to ask why the star-star station transformers shown in Fig. 11 are provided with delta windings. I know this is traditional practice and is done so as to ensure enough earth-fault current to operate protective relays, but if the transformers are of the 3-limb core type there will be enough fault current without the tertiary winding.

Mr. G. G. Smail: In Section 8 a suggestion appears to be made that there was a case for 33 kV stators at Blackwall Point because the machines were required to fit into a 33 kV network, but that actually an 11 kV stator with a step-up transformer was used, purely with the object of reducing the short-circuit duty on the switchgear. I have always understood that the 33 kV stator is more costly than the 11 kV one and is, in fact, equivalent to the combined cost of the 11 kV stator and step-up transformer. This being the case, I am of the opinion that the low-voltage stator and step-up transformer combination would be preferred wherever a connection at 33 kV or above was required.

At Littlebrook, Cliff Quay and Poole, the alternators were connected at 132 kV. Reference to Table 6C shows that at each of these places considerable trouble was experienced with

the 132 kV switchgear, and I should like to know the nature of the trouble at each station. It is noticeable that no trouble appears to have been experienced with the 33 kV switchgear at Blackwall Point or Earley, where 33 kV switchgear was also employed for two of the sets and 132 kV switchgear of the bulk-oil type for the third.

The authors refer briefly to a type of control panel for the electrical control room in which the relay panels are mounted behind the control panels. Such an arrangement has two disadvantages: first the relay panels are at a considerable distance from the switchgear instead of being as close as possible thereto, in order to reduce current-transformer burdens, and secondly the extreme length of the control panels becomes unwieldy. The modern trend is to install relay panels as near as possible to the switchgear and to provide control panels of small dimensions employing miniature components.

Extreme miniaturization can be achieved by providing a central alarm annunciation scheme, common to the whole of the switchgear installation, and to use components which are of extremely small dimensions which have been tried out in service over many years in telephone practice.

[The authors' reply to the above discussion will be found on page 496.]

SOUTH-WEST SCOTLAND SUB-CENTRE, AT GLASGOW, 20TH JANUARY, 1954

Mr. D. H. Campbell: Artists' impressions of the stations at Cliff Quay and Poole were widely publicized by the B.E.A. some years ago and certainly they were much more impressive externally than the rather utilitarian Braehead, for instance. Was the architectural design specially influenced by local authorities or the Fine Arts Commission, and, if so, to what extent would this be reflected in the cost?

[The authors' reply to the above discussion will be found on page 496.]

EAST MIDLAND CENTRE, AT NOTTINGHAM, 16TH FEBRUARY, 1954

Mr. O. S. Woods: I believe that consideration must first be given to reliability, overall economy and simplicity of design, with which the authors agree, but they go on to say that, nevertheless, four out of the five stations have appeared among the ten most efficient stations in the B.E.A. list. I think they are guilty of an understatement: it was because of these factors, in my opinion, that reliability was obtained over such a long period.

The authors favour central evaporation plant. Do they still hold that view when they talk about unit arrangements? I think it is correct to say that the details of feed-water treatment plant are not yet fully resolved by all designers. The paper does not include details of the operations required to treat the water on the two kinds of plant at Poole, both working at 100% duty.

I note in Section 9.1 that some very interesting tests were carried out at Earley to consider the effect of reducing the three-shift operation to two-shift. The authors say that the station efficiency drops from 26·4% to 25·33% when operated on two shifts. I say that a quarter of this loss is contributed by starting up the boilers—this appears to be another feature not fully resolved.

I take exception to the loose definition of the operating control room as one which is essential only to the operation of the station, and therefore contains only controls essential to operating the generators and dispatching loads. Surely it is essential to control in addition the boiler, the turbine and the alternators? I should like to suggest bringing together these three elements of control and putting them in a properly designed plant control-room on the operating floor of the station, where there are all the necessary features for the control of the plant in one place. There would then be less likelihood of conflicting information originating from different people.

Mr. D. D. McIntyre: Reference has been made by one of the previous speakers to the use of backing rings in butt-welded joints. These form a very desirable feature to enable a full penetration of the weld metal to be made and also to prevent weld spatter or obstructions passing into the bore of the pipe. In addition, they materially assist in lining up the pipes in the course of erection, and anyone who has had first-hand experience in assembling heavy butt-welded pipes in the air would appreciate this facility. The obstruction in the pipe is very small as the constant thickness of the backing ring is used throughout the system, and in the past this has not been considered detrimental. We are, however, carrying out welds without backing rings in certain instances, but this is a very small proportion of the total number which have been done and put into service.

Reference is made to the use of ferritic steel for use on work at 1 050° F. I assume that this refers to $2\frac{1}{4}$% chromium, but so far there are no available data to show how this performs in this country—either during manufacture or in service. The use of a ferritic steel is governed by the strength of the weld metal which can be deposited, and which—when subjected to suitable heat treatment—shows the properties required for high-temperature work. On one job which is at present being manufactured, this weakness is so pronounced that flanges and bolts are being fitted at each butt joint, to act as a mechanical aid and to ensure that the weld metal is in compression whilst in service.

In the case of austenitic steel it could be stated clearly that there is no difficulty in depositing a weld of full strength provided that a correct technique is adopted for the welding and suitable austenitic steel is used for the pipes and fittings.

Mr. N. F. Newey: The authors mention that it is their usual practice for high-pressure valves to be butt-welded into the lines. What is their opinion of butt-welding as opposed to flanges seal-welded?

Mr. J. Haynes: With reference to the development of four of the stations described in the paper, it is striking that only one of them was designed for reheating. Why is reheating treated as something abnormal and not included in every design? Is it on consideration of the probable load factor of the station?

I was interested to note how the noise caused by the orifice in the feed pumps leak-off at Littlebrook was overcome. I have had the experience of overcoming a similar noise by putting two orifice plates in series.

Mr. A. G. Connell: The authors have indicated large losses on the high-pressure steam pipes, and I wonder how this was assessed. In the light of 1954 experience, is it the case that steam feed pumps are out of the question, and do the operators still like to have a steam feed pump available?

Messrs. W. Price, W. Fenwick and **W. Warren** also contributed to the discussion at Nottingham.

[The authors' reply to the above discussion will be found overleaf.

NORTH MIDLAND CENTRE, AT YORK, 30TH MARCH, 1954

Mr. G. T. Shepherd: With reference to Fig. 1, most, if not all, turbines are capable of more than rated load, owing to design tolerance, etc. This is an advantage in the case of 80% economic rated sets, since it merely moves the economic point above 80% and results in less by-passing at higher loads. In the case of 100% economic rated sets, however, it results in an increased throttling loss at the stop valve. This appears to be a further advantage of the 80% economic rated machine that has not previously been mentioned.

The straight-cycle stations in the paper are all steam range stations. This, in the case of 2-shift working, allows of easier running-up conditions owing to hot steam being available. In all cases it must give greater availability, and it would be interesting to know the economics that justify the unit system in, say, a straight 900 lb/in^2 900°F station. I suggest that the capital cost of a simple steam tie-main would be far more than recovered by increased availability and ease of operation.

I note that only Earley has unit circulating-water pumps. At Skelton Grange it is found to be far more economical to run the condensers with a circulating-water rise of about 20° F and a corresponding reduction of water. The saving in auxiliary power consumption more than balances the almost negligible rise in back-pressures. Thus, the flexibility of a common bus-bar-main is advocated in order to ensure most economical working of the cooling-water system.

The steam temperature drop from boilers to turbines at Skelton Grange is so small that commercial instruments actually show a rise, hence emphasizing the importance of thermometer pocket design and position for accurate measurement of temperatures of this order. This very small drop confirms the authors' views on temperature drop allowances of 15–25°F being too liberal.

The authors have queried the need for a steam pressure gauge in the operating room. Such a gauge, or a boiler automatic control pressure gauge, where used, must be considered a necessity. It is agreed that under normal circumstances it is the duty of the boiler house operatives to maintain constant steam pressure. In times of stress, however, a pressure gauge of some description is essential. It is difficult to imagine the control room taking conflicting action with the boiler house if the steam pressure is, say, 100 lb/in^2 down and dropping fast.

Mr. J. G. Craven: A glance at Table 6A indicates an amazing increase in the efficiency of British power stations during the past half-century. I find on referring to one of my early-day note-books that for the week ending 16th December, 1908, Carville power station sent out 2 522 300 kWh, and the coal required per kilowatt-hour sent out was 2·76 lb, with a maximum load of 27 000 kW at 0·98 power factor.

At this time Carville was one of our largest and most efficient power stations, but applying this coal figure to Cliff Quay in Table 6A, it appears that, instead of consuming 347 500 tons of fuel in 6 months at 1·152 lb of coal per kilowatt-hour sent out, the figure would have been some 830 000 tons, and I suggest that without the remarkable increase in efficiency of combustion, boiler, and turbine plant (with fuel at its present-day cost), no one could afford to use electricity either for industrial or domestic purposes.

I should like to ask the authors what they consider mainly contributes to this increased efficiency.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. S. D. Whetman and **A. E. Powell** (*in reply*): The first part of our reply may be classified as "General," after which matters are dealt with under appropriate headings.

On the subject of layout Mr. Gylee referred to the longitudinal versus transverse arrangement of turbo-alternators. This is determined sometimes by the shape of the site, but more usually it is economical to match the turbine and boiler-house lengths. The longitudinal turbine arrangement reduces the span of the overhead crane, but on the unit turbine and boiler installations the transverse turbine arrangement is usual. We agree that, technically, belt coal conveyors are much to be preferred to bucket conveyors where space is available, but there are places where some cognizance must be taken of architectural requirements.

The unit circulating-water pump at Earley has been mentioned by Mr. Weston and also by Mr. Shepherd, who points out the advantages of the busbar system. We agree with his remarks, and had the ultimate development of Earley been known at the outset the choice there would have been different. Mr. Berry refers to chlorination: where this has been installed it is for intermittent injection at the condenser inlets. It has since been added at Poole to clear the inlet culverts also.

References to the unit control centre were made by Mr. Palfreyman and Mr. Woods. We agree that this is the logical outcome of the unit boiler-turbine arrangement.

Dr. Bock asks for our views on the use of a house alternator, to make the supply independent of frequency changes. Whilst this may be justified in the case of some oversea stations which may become completely isolated, we do not consider them necessary in this country. At the higher steam temperatures and pressures they are less efficient and do not justify the space occupied. Also in reply to Dr. Bock we confirm that the location of the feed pumps at operating floor level has proved entirely satisfactory.

Mr. Weston referred to the choice of steam temperatures. The load factor at Blackwall Point in 1952 was in fact higher than that at Poole, but this was not expected as normal. Blackwall Point was expected to operate on a two-shift basis at a low load-factor, and on 30 MW turbines the efficiency at the higher temperature and pressure was not considered sufficient to outweigh the advantages of quicker starting. The results at Poole and elsewhere have proved the suitability of larger 900 lb/in^2 925° F machines for two-shift operation.

Some speakers have referred to the merits or demerits of the unit boiler-turbine system. Mr. Hywel Jones suggested that a unit layout made it desirable to increase the range of steam temperature control. This is rather outside the scope of the paper, but superheat control as normally applied is to reduce the temperature at maximum output, and quite a different device is required to increase the steam temperature to match the turbine metal temperatures at starting. Mr. Shepherd refers to the advantage of a steam range in providing steam which is hotter than the casing of the turbine to be started. The justification of the unit arrangement at higher temperatures and pressures is its greater simplicity and saving in cost.

On the subject of reheating, several speakers have asked about its suitability for two-shift operation or at half-load. As Mr. Atkinson has said, there is no difficulty in operating the Littlebrook "B" machines, even with two boilers per turbine, and experience elsewhere has not revealed any difficulty in daily starts. We consider reheating justified on the larger machines, despite the fact that they may have to operate on a two-shift

basis for a large part of their life. Mr. Atkinson will no doubt be glad to note the current tendency for the use of reheat cycles on a wider scale on the installations now being planned.

To Mr. Marshall we would point out that the design reheat temperature at Littlebrook "B" is the same as the initial steam temperature, but it is not necessarily usual to reheat to the live steam temperature. As Mr. Marshall infers, this answer has to be obtained by an economic investigation of each case.

Mr. Arnold mentioned some points about efficiency. The power consumption of the auxiliaries is included in the station heat balance and is an important matter in considering auxiliary drives and in the comparison of different operating pressures. Worm drives are used for some purposes such as conveyor and lubricating-oil-pump drives to save space. We cannot make an economic case for the elimination of economizers on natural circulation boilers, and it is necessary to provide dust precipitators at the final boiler outlet and to design them accordingly. We agree that considerable space is required, and efforts to reduce this are proceeding. The draught loss caused by sharp changes of direction is a very small proportion of the total, and does not justify the extra space required for easier bends.

The alternator losses are of course a smaller proportion of the output on hydrogen-cooled alternators than on air-cooled ones. The difficulty in recovering them—as with transformer losses—is that the temperature difference is so small that the heat exchangers would not be economical.

In reply to Mr. Craven, the increased efficiency compared with the 1908 figures he quotes is attributed to the higher steam temperatures and pressures, greater combustion efficiency and improved plant designs.

In reply to Mr. Worland's comment that ash plants may affect the availability or thermal efficiency of power stations, we agree that this is true inasmuch as the boiler ash hopper and method of quenching may do so. In these stations the ash hoppers have not affected the availability, and the effect on efficiency is negligible.

Mr. Campbell referred to architecture. The conveyor arrangement at Poole was a voluntary concession to appearances, but otherwise the design was not influenced by local authorities or the Fine Arts Commission. A good appearance has been obtained by uniformity of window arrangement and a clean silhouette.

The Poole foundations were mentioned by Mr. Weston and Mr. Shepherd. If the problem arose again when an easier supply of materials and skilled labour existed, a cellular raft might well be the answer at the deeper end.

Turbines and Condensing Plant.

The remarks by Mr. Ecker and Mr. Thyer on Fig. 1 are answered by our reply to the London discussion.* In reply to Mr. Ecker, Mr. Pilling and Mr. Weston we have not yet sufficient evidence to prove that the turbine without a by-pass valve is more reliable or has a better rate of loading. Mr. Thirtle has also referred to the possibility of operating turbines only at full load; this we agree is possible and usual with the most efficient machines on the system, but over the whole life of the machine it is unlikely.

Mr. Marshall refers to the water sealing of turbine glands. The rapid starts achieved on the Poole turbines, since Fig. 15 was prepared, show that this is no handicap. An account of this was given in a paper by Hall and Brittin.†

The vacuum unloader to which Mr. Weston and Mr. Higginson refer is set to operate at a high condenser pressure. It has not operated "out of its turn," and load is not restored until the operator has reset.

In reply to Dr. Darlington, a water velocity of 5 ft/sec in the condensers was considered to be the economic value at Littlebrook "B." While there may be cases elsewhere justifying a higher velocity for sedimentation or other reasons, to our knowledge there has been no undue trouble at Littlebrook owing to settlement of silt.

The most recent data on starting-up experiments in British stations are given in the paper by Hall and Brittin, and with the varying conditions applicable to the different makes of plant and the different steam conditions, we suggest that it is essential that the programme of starting-up from cold or from an overnight shut-down should be determined individually for different installations using full instrumentation. It is, however, expected that the larger machines now being ordered will be suitable for two-shift operation.

Mr. Higginson, Mr. Thyer and Mr. Pilling refer to turbine governors. Satisfactory load-rejection tests have been made on the turbines with and without the overspeed relays where these are fitted; we see no objection to a supplementary governor control initiated by the electrical load.

Condensate and Feed Heating Systems.

References to de-aeration have been made by Dr. Darlington, Dr. Bock and Messrs. Pilling and Thirtle. The use of the main condenser for de-aeration has been satisfactory, although we agree that it relies on a completely leak-free installation between the condenser and the feed pumps. The make-up of demineralized water at Poole is introduced high up in the condenser, but not high enough to act as a spray condenser.

De-aerators operating at conditions slightly above atmospheric are being installed in certain of the newer power stations in this country, as mentioned by Dr. Darlington. We should, however, expect a better dissolved oxygen content from the condensers than the $0 \cdot 03\,cm^3$/litre mentioned by Dr. Bock.

In reply to Dr. Bock and Mr. Berry, the specification calls for a steam purity of not more than 1 part in 10^6, with boiler water concentration of 1 000 parts in 10^6. The boilers are usually operated at lower concentration with a consequent improvement in steam purity.

The provision for pure steam is in the form of scrubbers, or baffles and a collecting header in the boiler drums. Pure feed is derived first by control of the evaporator or demineralization plant output, and by provision for l.p. and h.p. chemical dosing on the feed system. There is no special arrangement for bleeding the condensate system.

In reply to Mr. Pilling and others, the lime-soda water softeners, followed by evaporation, have proved to be perfectly satisfactory.

In reply to Mr. Woods it is not possible to consider central evaporators at unit stations without departing from the unit principle, and similar evaporators would therefore be attached to each unit.

Feed Pumps.

Mr. Cooke refers to the design head and the use of hydraulic couplings. Different designers use different methods for computing the required head at maximum output which often give practically the same answer. We agree that if a margin is added for every contingency including low-frequency operation, the result may well be too high; but pumps properly designed to operate against boiler blow-off pressure will have a margin for low-frequency operation under otherwise normal circumstances.

It is doubtful whether the pump maker will add a margin to

* See 1953, 100, Part I, p. 253.

† HALL, J. S., and BRITTIN, A. F.: "Rapid Starting Technique—Some Significant Tests at Poole Power Station," *Proceedings of The Institution of Mechanical Engineers*, 1954, 168, p. 717.

the specified head, since it is necessary for him to meet the specification.

We assume that Mr. Farthing is referring to the silencing of the feed-pump leak-off. A plain multi-holed orifice plate was found to be satisfactory.

Variable-speed pumps are technically desirable, but at the speeds and outputs required the hydraulic coupling is only now becoming a possibility. The constant-speed pump has hitherto been accepted on the grounds of first cost and reliability.

The temperature-actuated leak-off is a less costly device than one based on a water meter suggested by Mr. Cooke, and we can confirm to Mr. Berry that it is sufficiently reliable to be used without any back-up device. The pump must of course be designed to accept a small rise of temperature, whatever the normal feed temperature may be.

In reply to Mr. Gylee and Mr. Connell we do not consider steam-driven feed pumps essential on a pulverized-fuel installation.

Pipework.

In reply to Mr. Thyer we confirm that the butt-welded joints have been free of maintenance.

All butt-welds incorporate backing rings. For alloy steel a pre-heat temperature between 400° F and 600° F was applied and maintained during the welding process. The welds were subsequently stress relieved at a temperature between 1 200° F and 1 300° F and were cooled down to 500° F at a rate of 300° F per hour per inch of wall thickness. The stress-relieving procedure for carbon steel is a little less rigorous. All welds on pipes of more than 4 in bore were made by the arc-welding process.

Mr. Eccles referred to the pipe joints at Littlebrook "B" and Poole. At both stations the valve joints are flanged and bolted with seal welds; the higher maximum temperature and two-shift operation do, in fact, make the conditions at Poole the more strenuous. Under both sets of conditions the butt-welded joint is considered more satisfactory, and where flanged joints are used it is advisable to make a periodic inspection of the bolts because of relaxation. We note that Mr. Hywel Jones prefers butt-welded joints at valves, and with satisfactory testing arrangements on the valve bodies we should agree with this, although a properly designed flanged joint should not give trouble with conservative steam conditions. Mr. Eccles also refers to the possibility of using a number of smaller-bore pipes. In the example he quotes sixteen 3 in pipes would be required to give the same steam velocity as one 12 in pipe. In fact, more smaller pipes may be necessary because of the effect of diameter on pressure drop. Usually a single pipe is the most economical arrangement.

In properly insulated ranges the temperature drop is, as Mr. Shepherd points out, extremely small. In reply to Mr. Connell we have not referred to large losses in steam ranges—on the other hand we suggest that the velocity might in some cases be increased.

Boilers.

Dr. Bock refers to the margin on the steaming capacity of the boiler plant. On a unit installation we agree that there is no justification for greater margin than is necessary to cater for poor fuel and the general deterioration of plant performance, but with a range pipe installation spare boiler capacity is justifiable. If the boilers in use are balanced with the load requirements there should be no difficulty in controlling the steam temperature.

We confirm that the net efficiency quoted on Table 6B is calculated on the net calorific value of the coal, which we think is the right method for acceptance tests, since it avoids the necessity for correction for variation in moisture and hydrogen content.

Mr. Hywell Jones suggests that a wider range of superheat control is desirable on a unit system. This is costly, since it involves a bigger superheater to give the temperature at lower outputs, followed by a bigger desuperheater to limit the temperature at higher loads. It is impossible to produce steam at the design temperature at very low loads without some form of boosting, and various methods are in use for dealing with this problem at starting up. Further information on starting-up procedure can be found in the paper by Hall and Brittin.* In reply to Mr. Pilling we should prefer the gas by-pass control on the grounds of simplicity, but it is not possible to use this alone over a very wide range without loss of efficiency. Pendant superheaters exist at Earley because the boiler was so designed before it was appropriated, but we should have preferred a self-draining design for two-shifting. At higher pressures and temperatures, however, it becomes difficult to arrange a completely self-draining superheater, and we should now confidently accept a pendant type.

The hydraulically operated soot-blowers at Blackwall Point have been quite satisfactory; our experience with electrically operated soot-blowers has also been satisfactory.

In reply to Messrs. Pilling, Weston and Thomas, there has been no trouble with either the plate or the tubular air-heaters. These were preferred to the regenerative type by the operators of these stations, but on other stations where the layout has indicated their desirability we have installed regenerative air-heaters. In considering the gas temperature at the air-heater outlet at Blackwall Point it must be borne in mind that these units are fired by pulverized fuel.

Mr. Cooke referred to the location of the mill feeders, which have frequently been at operating-floor level. Their location depends partly on the type of mill, but with the increasing tendency for remote operation from the control panel we see no objection to the feeder being under the observation of the plant attendant at mill level.

Mr. Higginson refers to the two-speed fans with damper control. This is not so inefficient as first it appears, since the motors do not normally operate at their higher speed. However, we agree that vane control can usually be justified, particularly where boilers may operate at lower ratings for long periods.

The economic justification for hydraulic couplings depends upon the anticipated loading conditions and other variables.

Generators.

In reply to Mr. Szwander and Mr. Abbott, we see no reason why 33 kV air-cooled generators should not be specified, provided that the possible lower impedance is acceptable, as at Earley. As Mr. Smail suggests, the 33 kV generator is more costly than one at 11 kV, but if 33 kV is required as a transmission voltage there may well be savings which justify it. In reply to Mr. Higginson we confirm that third-harmonic voltages did not affect the decision whether or not to generate at 33 kV.

Mr. Abbott referred to exciters. The gear-driven exciter does not increase the space occupied, since it is contained in the space required for rotor withdrawal. A special form of coupling is provided to prevent the transmission of vibration to the gears. A direct-driven a.c. generator on the main shaft is not in our view the best alternative, and if a separate drive is adopted we should prefer to take the supply to the motor-driven exciter from a transformer.

* HALL, J. S., and BRITTIN, A. F.: "Rapid Starting Technique—Some Significant Tests at Poole Power Station," *Proceedings of The Institution of Mechanical Engineers*, 1954, 168, p. 717.

Regarding hydrogen cooling we have not found it impossible to arrange the electrical controls to satisfy the Factory Act, but the arrangement of the purity indicator still presents a problem. Since the Littlebrook "B" machines were installed we have adopted bearing oil for shaft sealing as a normal arrangement.

We agree with Mr. Ross that an increase in the hydrogen pressure permits an increase in the alternator output at a slight loss of efficiency, but to take advantage of this the turbine must have a corresponding margin. It is more likely that the alternator and exciter as designed will have as much margin as the turbine. An increase in hydrogen pressure would, however, enable full load to be retained when the cooling water temperature is high, resulting in a higher hydrogen inlet temperature. The adoption of hydrogen cooling on smaller alternators is entirely a matter of economics, whilst the larger sizes now being constructed, such as 120 MW at 3 000 r.p.m., are made possible only by the adoption of hydrogen cooling.

Switchgear.

We agree with Mr. Palfreyman that very-high-voltage switchgear can be designed for any system fault rating. In the case of those power stations where alternative system voltages existed, the choice of generator switching voltage was in fact determined by the limitations of the lower-voltage system; there was never any doubt that switchgear was available to meet the requirements, but it was impracticable to rebuild the whole of the existing network. We agree that switching at 132 kV is most usually the obvious arrangement.

On larger stations we should consider the use of 6 kV as the major auxiliary voltage, as an alternative to 3·3 kV gear with a higher rating than used at present, but the final answer depends on the economics of each particular case. At either voltage the oil circuit-breaker is available.

We consider separate chambers for the auxiliary switchgear to be justified for the sake of cleanliness and the limitation of fire hazards by the exclusion of air and the enclosure of smoke.

In reply to Mr. Arnold, there is an omission in Fig. 10. The inter-busbar transformers do in fact contain tertiary windings.

In reply to Mr. Abbott and Mr. Szwander, we do not believe that the Meaford "A" arrangement which dispenses with station transformers can be satisfactorily adopted with generators larger than, say, 30 MW, owing to the limitations of the 11 kV switchgear which is at present available.

In reply to Messrs. Palfreyman and Connon, the methods of earthing the 3 kV and 415-volt systems are considered to give the greatest continuity of supply. These permit the supplies to be maintained with a single earth-fault on the system, so permitting standby plant to be started before the faulty equipment is isolated.

Table 6.

Messrs. Pilling and Weston have referred to the outages under the heading of "high eccentricity" on turbines. These were occasions of rough starts when it was decided to shut down rather than continue and risk a bent shaft—and on none of these occasions was there any permanent trouble. The outage time was taken up in examining couplings. As experience was gained the occurrences became less frequent.

Mr. Pilling referred to a similar point arising from Figs. 15 and 16. The eccentricity is checked at low speed because at this earlier stage of the run-up the temperature differences are more critical.

The milling plant at Littlebrook "B" compares badly with the others in Table "C" because there are only two main mills per boiler, and any outage on them results in a drop of load below 60 MW. The high load-factor at Littlebrook "B" also influenced this, if we bear in mind the definition of an "outage" as given in the paper. The outages were in the main a "development" trouble and must be offset against the desirability of a small mill for starting-up purposes on which Mr. Atkinson has commented.

In reply to Mr. Thyer we can confirm that all the boilers have passed a deferred efficiency test after six months' continuous operation, with results that were well within the specified $2\frac{1}{2}\%$ below guaranteed efficiency on a clean boiler. In fact, the figures quoted for the Blackwall Point boiler refer to a test made after six months' steaming without off-load cleaning; the results are better than the quoted guarantee for clean conditions. We expect them to operate for twelve months with no more cleaning than can be done on the low-temperature air-heaters at weekends. This is, however, entirely dependent on the type of coal, which has varied very considerably.

The 132 kV switchgear outages, to which Mr. Smail refers, were due in one case to an insulation failure and in the other two to operators' mistakes.

Costs.

We refer those speakers who have suggested that the capital costs might have been included in the paper to the "Report of the Committee of Enquiry into Economy in the Construction of Power Stations" (H.M. Stationery Office, 1953) which contains schedules of the overall dimensions and costs of these and other stations. No direct comparison of cost is possible. The cheapest station was the first to be built, i.e. Earley; and the dearest was the last, i.e. Blackwall Point, which cost, in pounds (sterling) per megawatt, just twice as much as Earley.

On the question of margins, these were fixed as a result of past experience and were thought to be economically justifiable.

DISCUSSION ON

"AN 8 MeV LINEAR ACCELERATOR FOR X-RAY THERAPY"*

Mr. W. J. Meredith (*communicated*): A 4 MeV accelerator of the kind mentioned in Section 7 of the paper has been in use at the Christie Hospital, Manchester. Since physical measurements were started on this machine in April, 1954, it has run almost continuously and with very little trouble. Detailed records have been kept since August, 1954, and from that time the equipment has run for 800 hours. During about one-third of that time the X-ray beam was switched on.

Since August, 1954, the machine has been used for half of the time on physical, radiobiological and radiochemical research, and for the other half on the treatment of patients. So far, 73 patients have been treated, each treatment calling for daily sessions over a period of three weeks. The highest number of patients under treatment at any one time was 25, and in the light of our present experience 50 patients per day could be handled.

In the early stages, the ignitrons gave some trouble, but since August, 1954, the replacement rate of all components has been very reasonable—three ignitrons, two magnetrons and three small valves. Some vacuum faults have been experienced, one of which caused the only real delay in the treatment of patients. This occurred when a diffusion pump had to be changed, and treatment was held up for one day. A fault in the water circulating pump caused minor hold-ups on about three occasions.

This catalogue of faults must not, however, be allowed to hide the excellence of this machine. Its behaviour has, in fact, been quite remarkable. Ever since the earliest days it has run more smoothly and steadily, and given far less trouble, than any of the conventional X-ray machines in our experience. Its X-ray output is high and is admirably steady and easily controlled. Mechanically the whole machine is well balanced, and accurate positioning of patients is easily attained.

Mr. G. R. Newbery (*communicated*): An up-to-date summary of operating experience with the 8 MeV equipment is given below:

(*a*) Total number of running hours from 29th January, 1953, to 14th February, 1955:

Degas	*Run h.v.*	*Expose*	*Filaments*
90·0 h	1 905·0 h	897·2 h	5 353·5 h

(*b*) Total number of running hours since start of treatment on 19th August, 1953:

Degas	*Run h.v.*	*Expose*	*Filaments*
63·6 h	1 427·6 h	659·9 h	4 357·8 h

(*c*) The magnetron at present in use has completed 89 hours at reduced h.v. supply and 1 760 hours at full h.v. supply. The standby magnetron has completed approximately 200 hours.

(*d*) A total of 31 ignitrons has been used since 29th January, 1953, of which 21 were used in the top position and ten in the bottom. The top ignitrons have run for an average of 100 hours, and bottom ignitrons have run for an average of 200 hours.

(*e*) Sixteen T41 thyratrons have been replaced in the Pirani relays.

(*f*) Six hydrogen thyratrons, type BT.83, have been replaced in the tripping unit.

(*g*) Two electron-gun filaments have been replaced.

(*h*) Three ionization-gauge heads have been replaced.

From August, 1953, to the end of January, 1955, approximately 430 patients started treatment on the machine. The total number of individual treatment fields given in the same period was nearly 9000. Approximately 40 patients are treated per day.

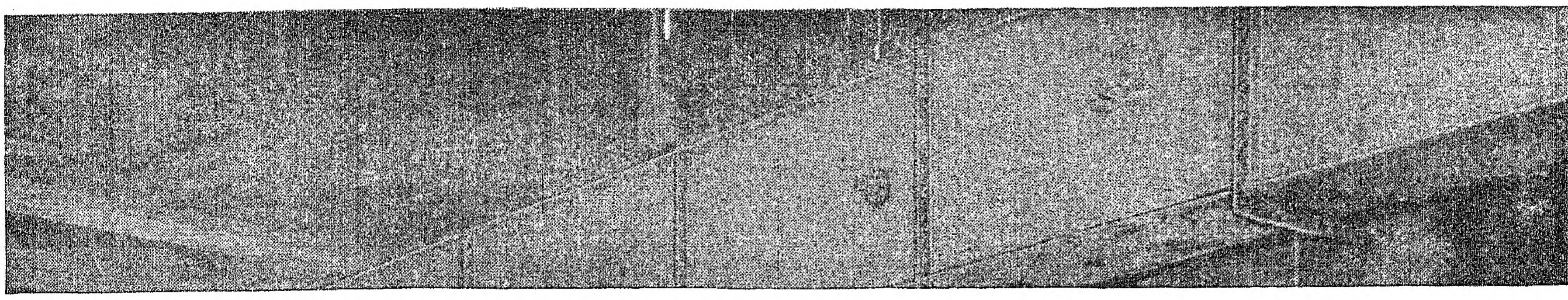
Mr. C. W. Miller (*in reply*): I am grateful to Messrs. Meredith and Newbery for their accounts of operational experience, and their contributions require little comment. Mr. Newbery, of course, deals with the 8 MeV equipment which is the main subject of the paper, and his account is a continuation of his contribution at the London meeting. The equipment has apparently been run at full high voltage for some further 800 hours since his first statement, and it is interesting to note that during this time there has been no failure of gun filament or magnetron. Indeed, the life of 1 760 hours from the present magnetron is most gratifying. The replacement rate of the T 41 thyratrons in the vacuum relays appears to have fallen a little, and a life of well over 2 000 hours can be deduced: this seems very reasonable.

Mr. Meredith refers to the 4 MeV equipment, which receives only passing mention in Section 7 of the paper. Several of these equipments, now known as Orthotrons, have been completed. In addition to the equipment at the Christie Hospital, identical machines have been installed at the Western General Hospital, Edinburgh, and at Mount Vernon Hospital, Middlesex, while other equipments are shortly to be installed in three hospitals in Australia. In addition, designs are available to utilize the same basic accelerator for industrial radiography and for irradiation processes for the sterilization of pharmaceuticals and the treatment of plastics.

As regards Mr. Meredith's operational experience, it is probably worth stating that this particular equipment was virtually a prototype model, and since Christie Hospital is so very close to the factory, much of the final testing was done at the hospital rather than in the works. It is therefore very pleasing that such a good account is given despite the minor difficulties which are inevitably associated with prototype equipment.

It is noted that, with both equipments, the lives of the ignitrons are unsatisfactory. They were, of course, not designed for this purpose, and as was stated in my reply to the London discussion, it had always been hoped that they would be replaced by an alternative switching valve. This has now become possible, and in our laboratory accelerator lives of over 2 000 hours have been obtained from hydrogen thyratrons used for this purpose; and future accelerators, including those to be installed in Australia, will be fitted with these valves.

* MILLER, C. W.: Paper No. 1619, March, 1954 (see 101, Part I, p. 207).



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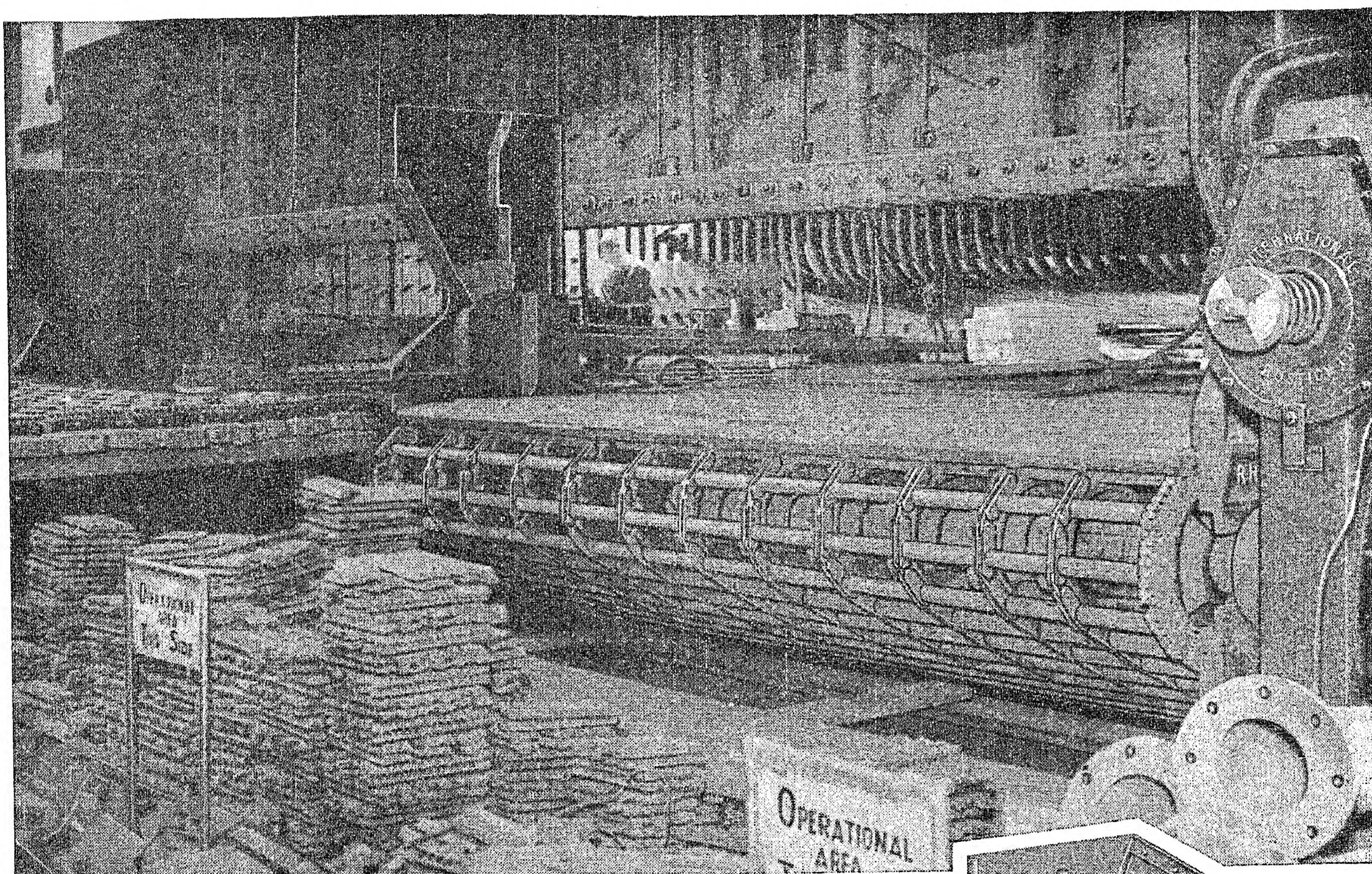

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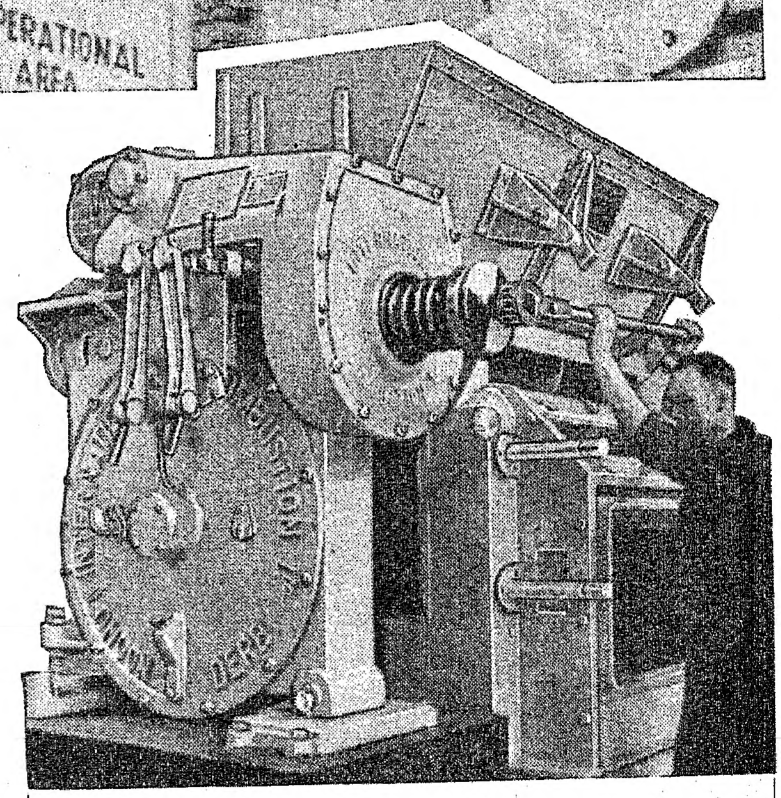

Top: A large 'L' type stoker with twin travelling grate during installation.

Below: Hand operation of small 'L' stoker grate during erection.

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PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, AUGUST 1955

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Example.—SMITH, J.: "Overhead Transmission Systems," *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).

Published by The Institution, Savoy Place, London, W.C.2. *Telephone:* Temple Bar 7676. *Telegrams:* "Voltampere, Phone, London."
Printed by Unwin Brothers Limited, Woking and London.